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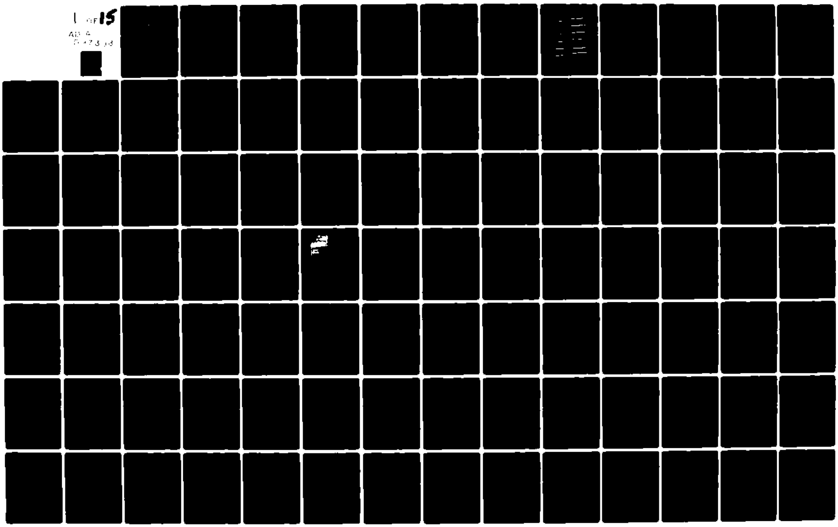

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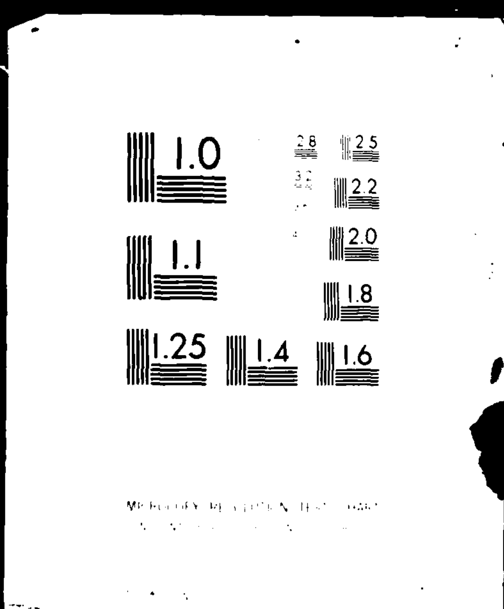

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USAF SUMMER FACULTY RESEARCH PROGRAM

1980

RESEARCH REPORTS

VOLUME 1

CONDUCTED BY

THE SOUTHEASTERN CENTER FOR ELECTRICAL ENGINEERING EDUCATION

PROF. WARREN D. PEELE
PROGRAM DIRECTOR, SCEEE

MAJ. RICHARD K. KOPKA
PROGRAM MANAGER, AFOSR

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The United States Air Force Summer Faculty Research Program (USAF-SFRP) is a program designed to introduce university, college, and technical institute faculty members to Air Force research. This is accomplished by the faculty members being selected on a nationally advertised competive basis for a ten-week assignment during the summer intercession to perform research at Air Force Laboratories/centers. Each assignment is in a subject area and at an

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Air Force facility mutually agreed upon by the faculty member and the Air Force. In addition to compensation and travel expenses, a cost of living allowance is also paid. The USAF-SFRP is sponsored by the Air Force Office of Scientific Research/Air Force Systems Command, United States Air Force, and is conducted by the Southeastern Center for Electrical Engineering Education, Inc.

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1980 USAF/SCEEE SUMMER FACULTY
RESEARCH PROGRAM

Conducted by

Southeastern Center for

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under

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RESEARCH REPORTS

Volume I of II

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Bolling Air Force Base

Washington, D.C.

by

Southeastern Center for
Electrical Engineering Education

October 1980

P R E F A C E

The United States Air Force Summer Faculty Research Program (USAF-SFRP) is a program designed to introduce university, college, and technical institute faculty members to Air Force research. This is accomplished by the faculty members being selected on a nationally advertised competitive basis for a ten-week assignment during the summer intercession to perform research at Air Force laboratories/centers. Each assignment is in a subject area and at an Air Force facility mutually agreed upon by the faculty member and the Air Force. In addition to compensation and travel expenses, a cost of living allowance is also paid. The USAF-SFRP is sponsored by the Air Force Office of Scientific Research/ Air Force Systems Command, United States Air Force, and is conducted by the Southeastern Center for Electrical Engineering Education, Inc.

The specific objectives of the 1980 USAF-SFRP are:

(1) To develop the basis for continuing research of interest to the Air Force at the faculty member's institution.

(2) To further the research objectives of the Air Force.

(3) To stimulate continuing relations among faculty members and their professional peers in the Air Force.

(4) To enhance the research interests and capabilities of scientific and engineering educators.

In the 1979 summer program, 70 faculty members participated, and in the 1980 program, 87 faculty members participated. These researchers were assigned to 25 USAF laboratories/centers across the country. This three-volume document is a compilation of the final reports written by the assigned faculty members about their summer research efforts.

Pages iii thru xiv deleted
per AFOSR, 8 May 81

1980 USAF/SCEEE SUMMER FACULTY RESEARCH PROGRAM

LIST OF PARTICIPANTS ~~Page 13~~

NAME/ADDRESS	DEGREE, SPECIALTY & LABORATORY ASSIGNMENT
Dr. David Williams Assistant Professor University of Texas/El Paso Dept. of Electrical Engineering El Paso, TX 79968 (915) 747-5470 [redacted]	Degree: PhD, Electrical Engineering, 1977 Specialty: Digital Image Assigned: AFWL (Kirtland) [redacted]
Dr. Paul Williams Assistant Professor University of Wisconsin/ Superior Superior, WI 54880 (715) 392-8101 [redacted]	Degree: PhD, Professional Studies, 1976 Specialty: Research & Evaluation Assigned: AFLC (Wright-Patterson) [redacted]
Dr. Edward Winkofsky Assistant Professor Virginia Polytechnic Institute & State Univ. Dept. of Business Administration Blacksburg, VA 24061 (703) 961-5083 [redacted]	Degree: PhD, Business, 1977 Specialty: Quantitative Analysis, Mathematical Optimization Assigned: AFAL (Wright-Patterson) [redacted]
Dr. George Worm Associate Professor Clemson University Dept. of Industrial Management Sirrine Hall Clemson, SC 29631 (803) 656-3499 [redacted]	Degree: PhD, Management Sciences, 1970 Specialty: Operations Research, Management Sciences, Math, & Statistics Assigned: AFBRMC (Wright-Patterson) [redacted]
Dr. Daniel Yannitell Associate Professor Louisiana State University Dept. of Mechanical Engineering Baton Rouge, LA 70803 (504) 388-5792 [redacted]	Degree: PhD, Theoretical & Applied Mech. 1967 Specialty: Applied Math, Fluid Mechanics Dynamics Assigned: AFRPL (Edwards) [redacted]
Dr. Yehoshua Zeevi Associate Professor Massachusetts Institute of Technology Dept. of Aeronautics & Astronics Cambridge, MA 02139 (617) 253-7759 [redacted]	Degree: PhD, Electronics Engineering, Specialty: Eye Movement Technology Assigned: AFHRL (Williams) [redacted]

PARTICIPANT LABORATORY ASSIGNMENT

1980 USAF/SCEEE SUMMER FACULTY RESEARCH PROGRAM

APL — AERO PROPULSION LABORATORY
(Wright-Patterson Air Force Base)

[redacted]hler - Oklahoma State University
2. Dr. James Lawler - University of Dayton
3. Dr. Albert Menard - Washingtio[redacted]ge
4. Dr. Dasara Rathnamma - US Naval Academy

AMRL — AEROSPACE MEDICAL RESEARCH LABORATORY
(Wright-Patterson Air Force Base)

[redacted] - University of the District of Columbia
2. Dr. Thiruvenkatasamy Govindaraj - [redacted]ty
3. Dr. Vernon Henderson - Grambling State University
4. Dr. Timothy Hight - Duke University
5. Dr. John Petersik - Southeast Missouri State University

AD — ARMAMENT DIVISION
[redacted]

1. Dr. Stanley Benton - Tulane U[redacted]
2. Dr. Karen Frair - Virginia Polytechnic Institute/State University
3. Dr. Lester Frair - Virginia Polytechnic Institute/State University
4. Dr. Royce Harbor - University of West Florida
5. Dr. James Sinclair - Rice University

AEDC — [redacted]VELOPMENT CENTER
(Arnold Air Force Station)

1. Dr. Arend Hagedoorn - Universi[redacted]da
2. Dr. Robert Kerce - David Lipscomb College

AL — AVIONICS LABORATORY
(Wright-Patterson Air Force Base)

1. Dr. Frank Brown - University of Kentucky
2. Dr. Samuel Ling - Wright State University

[redacted] University of [redacted]

4. Prof. Harry Nienhaus - University of South Florida
5. Dr. Edward Winkofsky - Virginia Polytechnic Institute/State University

BRMC — [redacted]AGEMENT CENTER
(Wright-Patterson Air Force Base)

1. Dr. Frederick Bear - Western C[redacted]
2. Dr. Sallye Benoit - Nicholls State University
3. Dr. Richard Burton - Duke University
4. Dr. George Worm - Clemson University

ESMC — EASTERN SPACE & MISSILE CENTER
(Patrick Air Force Base)

1. Dr. Venkateswararao Vemuri - State University of New York/Binghamton

PARTICIPANT LABORATORY ASSIGNMENT (Continued)

ESD	ELECTRONIC SYSTEMS DIVISION (Hanscom Air Force Base) 1. Dr. John Papageorgiou - University of Massachusetts/Boston
ESC	ENGINEERING & SERVICES CENTER (Tyndall Air Force Base) 1. Dr. Thomas Baseheart - University of Cincinnati 2. Dr. James Gossett - Cornell University 3. Dr. Thomas Higgins - Arizona State University 4. Dr. Thomas Mason - Florida A&M University 5. Dr. Lawrence Rude - Virginia Polytechnic Institute/State University
FDL	FLIGHT DYNAMICS LABORATORY (Wright-Patterson Air Force Base) 1. Dr. Franklin Eastep - North Carolina State University 2. Dr. Arthur Grainger - Atlanta University 3. Dr. Sherif Noah - Texas A&M University 4. Dr. Louise Raphael - Clark College 5. Dr. Kuldip Rattan - Wright State University 6. Dr. Shiva Singh - University of Kentucky 7. Dr. Akhouri Sinha - Purdue University
FJSRL	FRANK J. SEILER RESEARCH LABORATORY (USAF Academy) 1. Dr. Richard Deckro - Virginia Polytechnic Institute/State University 2. Dr. Howard Sherwood - University of Central Florida 3. Dr. Almon Turner - University of Detroit
GL	GEOPHYSICS LABORATORY (Hanscom Air Force Base) 1. Dr. Robert Armstrong - New Mexico State University 2. Dr. Stephen Berman - University of Oklahoma 3. Dr. David Cooke - University of Utah 4. Dr. Peter Hierl - Kansas University 5. Dr. George Peace - College of the Holy Cross 6. Dr. William Tucker - Florida A&M University
HRL/ASD	HUMAN RESOURCES LABORATORY/ADVANCED SYSTEMS DIVISION (Wright-Patterson Air Force Base) 1. Dr. Larry Wall - New Mexico State University 2. Dr. Richard Warren - State University College/Buffalo
HRL/FTD	HUMAN RESOURCES LABORATORY/FLYING TRAINING DIVISION (Williams Air Force Base) 1. Prof. Marshall Waller - George Washington University 2. Dr. Yehoshua Zeevi - Massachusetts Institute of Technology
HRL/PRD	HUMAN RESOURCES LABORATORY/PERSONNEL RESEARCH DIVISION (Brooks Air Force Base) 1. Dr. Howard Alford - Morgan State University 2. Dr. Richard Christ - New Mexico State University 3. Dr. Philip Tolin - Central Washington University

PARTICIPANT LABORATORY ASSIGNMENT (Continued)

HRL/TTD	HUMAN RESOURCES LABORATORY/TECHNICAL TRAINING DIVISION (Lowry Air Force Base) 1. Dr. Barbara Lindauer - Miami University
LMDC	LEADERSHIP & MANAGEMENT DEVELOPMENT CENTER (Maxwell Air Force Base) 1. Dr. Edward Conlon - Georgia Institute of Technology 2. Dr. Thomas Petrie - University of Nebraska/Omaha
LC	LOGISTICS COMMAND (Wright-Patterson Air Force Base) 1. Dr. Paul Williams - University of Wisconsin/Superior
LMC	LOGISTICS MANAGEMENT CENTER (Gunter Air Force Station) 1. Dr. Andrew Hargrove - Tuskegee Institute 2. Dr. James Patterson - Clemson University
ML	MATERIALS LABORATORY (Wright-Patterson Air Force Base) 1. Dr. Billy Covington - Sam Houston State University 2. Dr. Charles Falkner - University of Wisconsin 3. Dr. Michael Hyer - Virginia Polytechnic Institute/State University 4. Dr. Francis Loo - Clarkson College of Technology 5. Dr. Joseph Schmidt - Memphis State University
RPL	ROCKET PROPULSION LABORATORY (Edwards Air Force Base) 1. Dr. Joseph Chiang - State University of New York College/Oneonta 2. Dr. Chong Jin Park - San Diego State University 3. Dr. Daniel Yannitell - Louisiana State University
RADC	ROME AIR DEVELOPMENT CENTER (Griffiss Air Force Base) 1. Dr. Caroline Eastman - Florida State University 2. Dr. Edward Lee - Wayne State University 3. Dr. Lonnie Ludeman - New Mexico State University 4. Dr. Francis Merat - Case Western Reserve University 5. Dr. Eugene Moriarty - San Jose State University
RADC/ET	ROME AIR DEVELOPMENT CENTER (Hanscom Air Force Base) 1. Dr. Timothy Anderson - University of Florida 2. Dr. Charles Smith - University of Texas/Arlington
SAM	SCHOOL OF AEROSPACE MEDICINE (Brooks Air Force Base) 1. Dr. Craig Daniels - University of Hartford 2. Dr. Howard Duncan - North Carolina Central University 3. Dr. Walter Kuklinski - Texas A&M University 4. Dr. Leland Morgans - University of Arkansas/Little Rock 5. Dr. Marvin Riedesel - University of New Mexico

PARTICIPANT LABORATORY ASSIGNMENT (Continued)

WL

WEAPONS LABORATORY
(Kirtland Air Force Base)

1. Dr. Richard Fragaszy - San Diego State University
2. Dr. Rafael Jimenez-Perez - University of Puerto Rico
3. Dr. Richard McCluskey - Clarkson College
4. Dr. Gerald McIvor - Illinois Institute of Technology
5. Dr. James Steelman - New Mexico State University
6. Dr. David Williams - University of Texas/El Pasco

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FINAL REPORT

THE HUMAN RESOURCES LABORATORY MANAGEMENT MODEL FOR INCREASING R&D PRODUCTIVITY

Prepared by: Dr. Howard L. Alford

Academic Rank: Professor

Department and University: Department of Business Administration, Morgan State University

Research Location: United States Air Force Human Resources Laboratory, Technical Services Division, Brooks AFB, Texas

Date: August 8, 1980

Contract No: F49620-79-C-0038

THE US AIR FORCE HUMAN RESOURCES LABORATORY MANAGEMENT MODEL FOR INCREASING R&D PRODUCTIVITY

by

Howard L. Alford

ABSTRACT

The question of the uniqueness of the AFHRL Laboratory Operations Center (MIS) was investigated. A model flow chart of the word processing component and data entry/data flow was developed and discussed. Results show that management is committed to advancing an effective, quality Management Information System which includes the recommendations of a cross section of task scientists, administrators and technicians. Some manual tasks and office procedures are being updated and automated. Opinions of a diversified group of employees regarding the LOC were discussed. Tendered were suggestions and implications for further research.

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Particular appreciation is tendered to Colonel Harold B. Powell and Mr Robert B. Bunker; the latter, not only for suggesting this area of research, but also, for his useful collaboration and guidance.

Also, he would like to acknowledge many helpful discussions with Col Tyree H. Newton, Dr. Malcolm Ree, Dr Joe Ward, and 1/Lt Dave Roberts.

Finally, he appreciates the assistance of Mr Jim Souter, Mr Amos Johnson, Mr Morton Fischer, 1/Lt Lynn Scott, and Mr Joe Muniz, the secretarial staff, and many additional employees at the AFHRL.

1. BACKGROUND

The AFHRL has been seriously interested in management information systems since 1973 when it conducted a study in cooperation with the University of Texas on the feasibility of establishing an on-line management information system within the Laboratory.

Like many R&D organizations, the AFHRL in examining its communication and information needs, found the problem to be of several dimensions. The challenge to cope with increasing quantities of technical information and reporting, together with the factors of duplication, workloads, accuracy, relevance and timeliness, became somewhat intensified when also recognizing organizational needs. Added to this was the serious need for management to consider the needs of scientists in conducting, directing, and documenting scientific efforts. Decisions need to be made on complete, accurate, and updated data.

Researchers found it would be feasible to standardize certain information files with the Laboratory and as a result, a management information systems office was established within AFHRL and given sole responsibility for gathering data and furnishing it to the staff and the divisions.

The concept for a Laboratory Operations Center (LOC) was first developed at AFHRL. A feasibility study in the use of a data base management system for the Laboratory environment was conducted at the Laboratory during 1973 and 1974. Results of this study were published in several technical reports in 1975. Much of this early investigative study was performed by Dr Joe Ward, Mr Joe Muniz, and Capt James Sells.

Word processing is the production and development of written communications through the combined use of systems management procedures, computerized and automated technology, and skillfully trained personnel. The conception, however, of word processing presents an advanced effort to introduce and employ modern technology into the office environ. This process requires substantive refashion of office structure and procedures.

Word processing is one result brought on by automation as many organizations, both public and private, began during the first part of the last decade to exchange their electric typewriters for computerized word processing equipment. With this advance, came more and more eqipment change. The principle of "one secretary-to-one-boss" institution changed also.

Initially, the concept was for the secretarial function to be divided into two basic job related tasks. First, the typing specialist or correspondence secretary, and second, the administrative secretary. Typing specialists were placed in the "word processing centers" which were staffed by correspondence secretaries only. Accommodating the entire typing needs was the workload of these centers. Administrative secretaries supported two or more principals, performing all their non-typing support activities. Subsequently, sheer necessity ignited an evaluation into cluster and satellite formations, whose word processing centers dispensed all the secretarial requirements of principals surrounding them.

Currently, both configurations are in operation and, in some instances, modifications of both. Whatever the case, the automatic typewriter has already forced a realignment of office labor. Thomas J. Anderson and William R. Trotter have suggested that only in recent years has management begun to recognize the enormous cost of managing information. Generally, the cost of managing information in many organizations is exceeded only by personnel, material and transportation costs. In government and some service type organizations, it has been suggested that the percent of the budget devoted to information management is frequently second only to that of personnel.

The spiraling cost of written communications are the consequences of various eventualities. These conditions include but are not limited to the following:

There are more people generating paper work.

There are relatively fewer office workers to perform these tasks.

Clerical productivity has not risen sharply during recent decades, and wages and salaries for office workers have continued to increase.

Figure 1-1 represents one concept of the total administrative system for word processing.

Reduction of office costs, improving the quality of work performed, and diminished turn around time of work produced have been made possible with word processing. By 1975 the US Army found clerical support savings to range from 15 to 30 percent. Other estimates have been as high as 40 percent savings in secretarial and typing costs. The percentage saved is determined by degree to which the office is systematized and automated. More data, however, is needed

to verify savings accruing to professional staff from word processing. It has been suggested that these savings dwarf those associated with support staff.

At the United States Air Force Human Resources Laboratory (AFHRL), word processing is administered by the Technical Services Division. Word processing is only one part of a multi-component management information system.

The automatic typewriter presaged the word processing system and has begun to merge with data processing. Simple keyboard operations do the typing, data processing, filing in-memory, or, in the case of computer output to micrographics (COM) microfilming. Simultaneously, reprographics together with facsimile transmission are merging into the system. Electronic mail is becoming more cost effective, and other elements of the clerical and administrative support system, cause a total system to develop and maintain the facility with which to support a diversity of administrative functions (see Figure 1-1). Automated equipment can be located in traditional unstructured offices, words can be processed, and savings can accrue. Approximately 80% of the savings associated with word processing, however, can be attributed to an integrated system design. This leaves 20 percent of the savings which can be accredited to automated equipment only. When written communications functions and highly skilled specialists are placed in a structured environment to assume responsibility for specific functions as shown in Figure 1-2, the systems approach is applied.

Employees performing tasks in written communications are specialists in grammatical construction, correspondence procedures, and in the conceptualizaion and operation of electronic equipment. Personnel serving in the administrative support component are specialists in concomitant services including filing and retrieval, travel scheduling, receptionist duties, telephone use, conference preparations, duplication and distribution and/or mail service.

One rule of the thumb suggests that an office which generates from 4000 to 6500 pages annually would find it economically feasible to consider automated equipment. When the total volume exceeds 16,000 pages per year, and associate factors are cogent, it is compelling to consider a systems approach to word processing.

The cost-savings potential of the total system approach is continuously

Figure I-1 A Total Administrative System

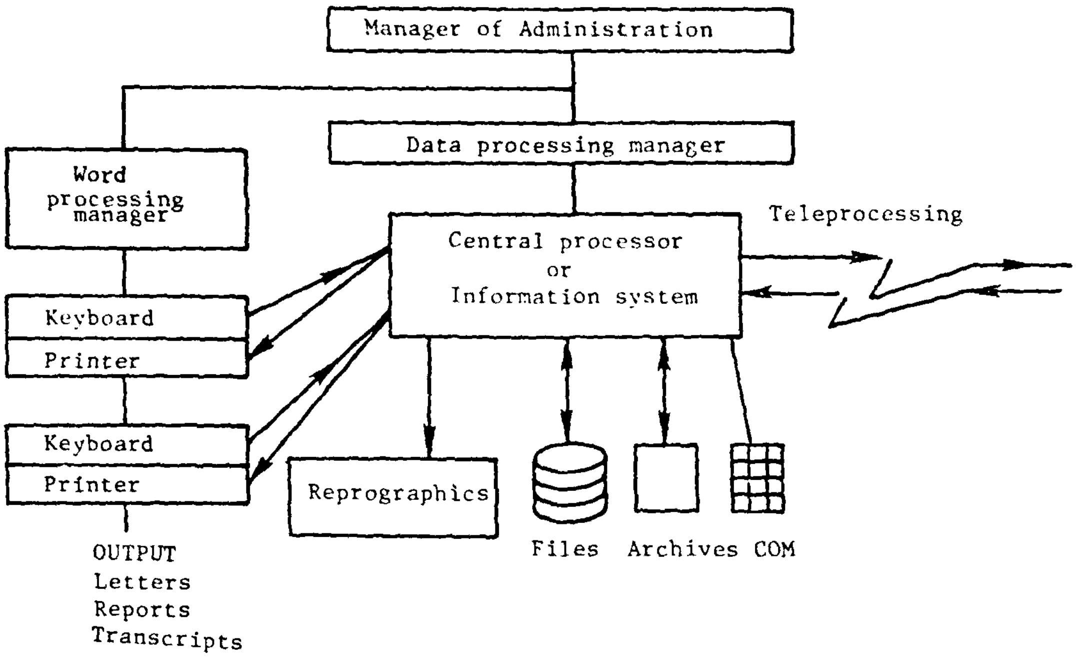
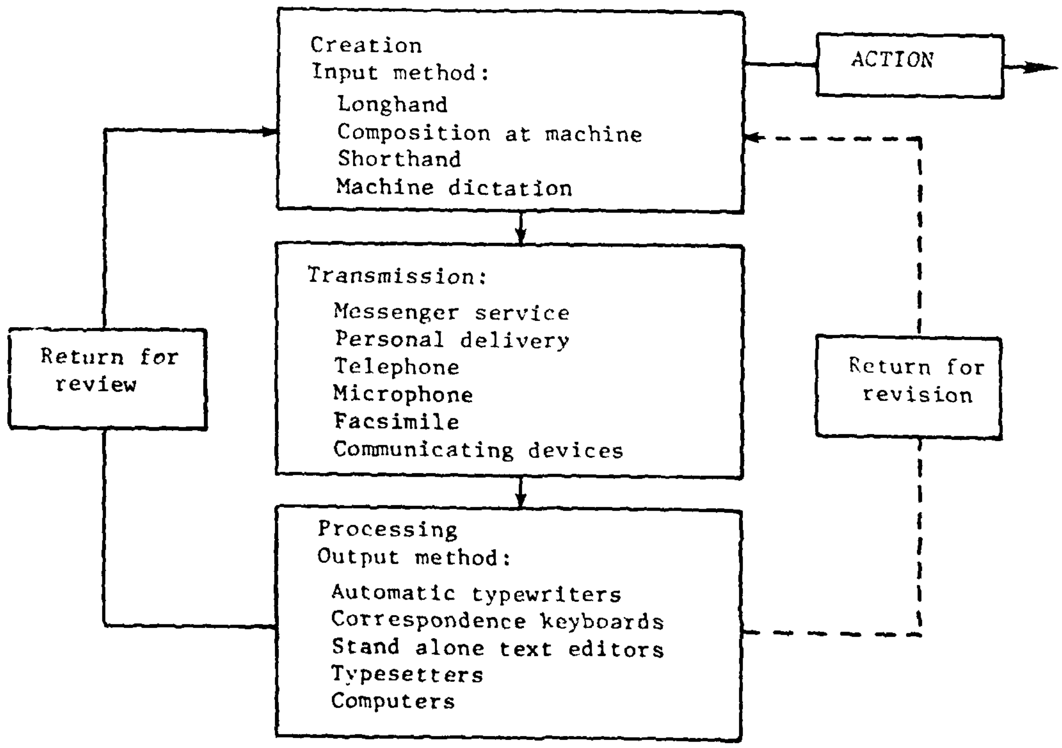


Figure I-2 Word Processing As a System



grossly unrefined. Tremendous savings will be found at cross over points, points at which it becomes cost-effective to automate. A system is viewed as a collection of units or modules that interact with each other according to a partially or totally specified plan (Lientz, 1975).

Below is a brief review of the seven basic applications of word processing.

1) Transcription of Materials: Originators of documents dictate into a magnetic medium, and this information is subsequently transcribed by a word processing specialist. Procedures save the time of both the originator and the supportive staff. The originator can, with appropriate equipment, dictate in the office or away from the office. No secretarial time is consumed in taking dictation, and materials can be scheduled for transcription on a systematic basis.

2) Repetitive Communications: Exact original copies of communications, such as form letters, are processed on automated equipment. These copies do not vary.

3) Combination of repetitive and variable communications: Personalized communications are produced by automatically appended variable information such as names, dates, quantities or other data to stored paragraphs.

4) Text Preparation: Documents such as manuals, reports, manuscripts, proposal, contracts, abstracts, and other extensive communications that require editing, amendments, deletions, and revision are input into the word processor. The material may be retrieved for review and revisions and a hard copy is produced. This procedure is duplicated as many times as is necessary.

5) Communications requiring immediate turn-around time. Materials are keyboarded at first-draft speed, and the computer is given instructions for formating. Material is then reviewed on the video scanner, and the output mechanism produces a review copy or final copy.

6) Composition and typesetting: The word processor is employed to record copy for setting and preparing type along with the instructions. The material, recorded on magnetic media or paper tape, goes to a composing typewriter, photocomposition device, or typesetter.

7) Systems Use: The word processor produces information in accordance with preprogrammed procedures and guidelines, performs basic information retrieval functions, automatically produces documents, or computes limited calculations in conjunction with the production of communications. Figure 1-2

represents one conception of the word processing system.

Equipment used in word processing includes input or (dictation) equipment and output on keyboard equipment. Also used are devices for accessing computers and copiers and facsimile transmission equipment. This and other equipment is used as suggested by Walter A. Kleinschrod, depending upon the level of complexity and sophistication of the system.

The input comprises three basic catagories of dictation equipment: 1) portable, 2) desk top, and 3) remote or centralized located recorders. Some variety of media is used with this equipment, including tapes, small disks, belts, and magnetic cassettes. (see Figure 1-2).

Five basic categories of word processors comprise the keyboard equipment. These five are: the automatic typewriters, correspondence keyboard, stand-alone text editors, composition and typesetting, and computers. (see Figure 1-2).

While progress is documented, word processing is barely out of its infancy. Indications are that word processing is becoming an integral part of the office and is projected to play an even broader role in the future. Projections are for less need for manual skills, and persons entering the field will be expected to acquire or possess a knowledge of management techniques, and an understanding of the structure and operations of organizations. Individuals with an interest in pursuing word processing should acquire a background in the fundamentals of electronic data processing and become familiar with the machines and systems used in word processing.

Four projected uses of this technological forecast include these listed below:

1) Automated typing systems with increased self-contained intelligence and more rapid print-out capabilities.

2) Communication typewriters or terminals connected to computers in all large offices and even some small offices.

3) Common use of interface with photo typesetting and optical character recognition, and

4) Increased flexibility in word processing systems, with telephones used to interface nation or worldwide, and to link networks of word processing systems.

II. INTRODUCTION

The Air Force Systems Command is composed of thirteen (13) associations of Research and Development (R&D) laboratories. These laboratories were established to investigate and explore frontiers; observe phenomena, new frontiers of technology; perform technical consultations; seek problem resolution, and specific practical solutions to very real challenges. Also, the Labs are designed to research alternative approaches for eliminating deficiencies and satisfying requirements on a timely basis. While the Air Force Systems Command is decentralized, each location in the Systems Command is highly specialized. This unique organizational feature promotes special configurations, research projects, and unparaqoned studies. The Air Force Human Resource Laboratory operates in a complex environment which parallels that of the Air Force Systems Command.

The AFHRL Annual Report FY 79 contains the following mission statement:

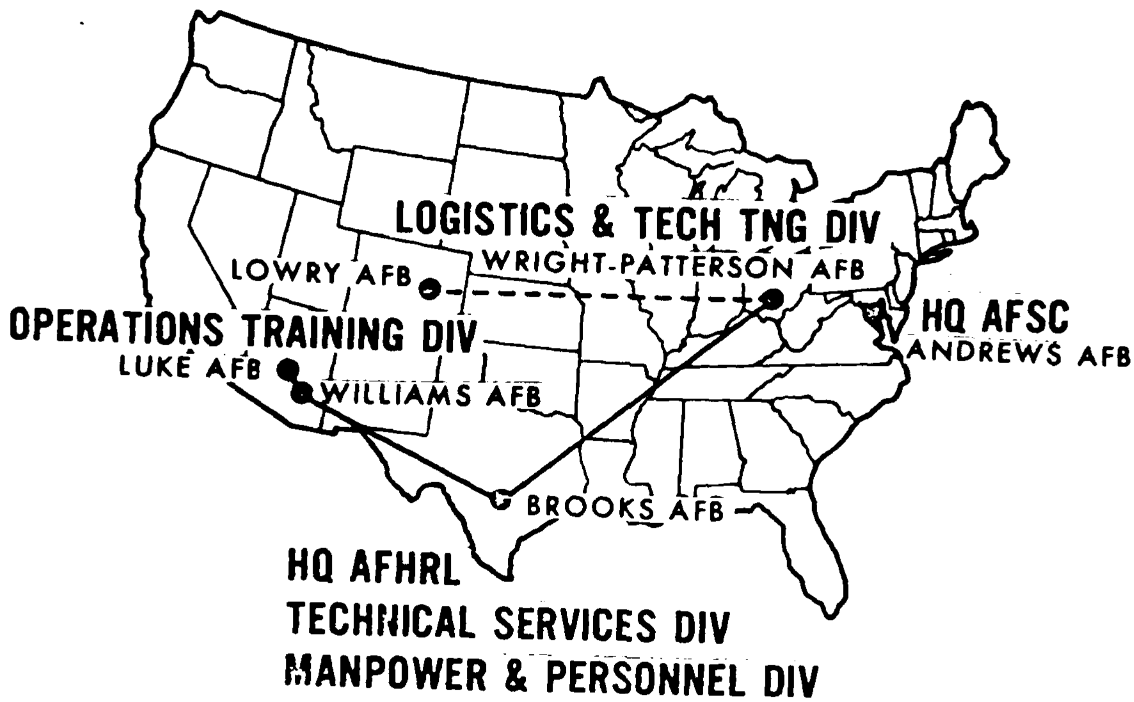
> "The AFHRL mission is broader than those of most other technology laboratories of AFSC. The hardware laboratories are almost entirely concerned with technological development; but hardware technology development is the only one of the responsibilities of AFHRL. Of equal importance in AFHRL's mission is the development of information for uses in making management and policy decisions on selection, training and personnel matters. This effort in human resources technology is most important because the largest single item in the Department of Defense budget is the cost of personnel and the associated costs of training and administratively supporting the personnel force."

In October 1979, AFHRL was reorganized into a Headquarters, four divisions and four operating locations. The four locations comprise Brooks AFB, Texas, Williams AFB, Arizona, Luke AFB, Arizona, Lowry AFB, Colorado and Wright-Patterson AFB, Ohio. Figure II-1 below shows the AFHRL organizational structure.

The Comptroller General of the United States made a "Report to the Congress" (FGMSD-79-17) dated April 6, 1979 during which it was suggested that Federal productivity suffered because word processing was not well managed.

The report cited advanced technology in office machines, secretarial functions and other breakthroughs which offer potentially more efficient and economical output of written communication. According to the report, the Federal Government employs more than 171,000 secretaries, with an annual salary outlay of over $1.5 billion and suggested this force could be reduced in numbers without decreasing the quality of services rendered.

Figure II-1 The Air Force Human Resources Laboratory Organizational Structure



The report also suggested that most federal agencies were not complying with regulations covering management of word processing equipment which cost about $80 million in fiscal 1977 and is expected to exceed $300 million by 1982. The question of demonstrating increased productivity and cost effectiveness was raised and it was felt that agencies needed to perform the following:

Feasibility studies, including the gathering of baseline productivity data;

Cost benefits and cost effectiveness studies of alternative equipment configuration;

Planning studies of the new system's effect on personnel; and

Post installation reviews comparing new productivity statistics with the base line data.

The report cited failure to use modern machinery, but made note of a few isolated examples of well managed productive word processing systems, such as the one being employed by the Social Security Administration's bureau of data processing.

Several recommendations were designed to assist agencies in upgrading and accelerating improvements in the management of word processing. A key element addressed was the need to develop model and standardized handbooks to aid agencies in operating these systems. Also, the issuance of guidelines for implementing and monitoring automated systems and the need to pay careful attention to personnel planning and management of the system.

III. OBJECTIVES

The main objective of this research was to investigate the question of labor intensity of AFHRL personnel and to identify data which would show the distribution of time spent on tasks which were labeled direct mission and indirect mission related activities. Another objective was to identify tasks which scientists or technicians and administrators were presently performing which might best be automated. Efforts were exerted to secure this data and to describe a model for predictive productivity. Listed below are the specific statements of objectives for this research.

1. An analysis of the history of the Laboratory and the utilization of scientific, technical, and administrative personnel will be conducted. This research will provide the distribution (direct and indirect efforts) and documentation of the administrative, scientific, and engineering effort. Data will be developed to establish and analyze productivity and efficiency trends.

2. The description of a proposed model to predict productivity trends will be developed. A critique of this model for sound scientific systems management decision effectiveness will be conducted. This data are expected to identify strengths and weaknesses in the model, and recommendations are anticipated. These recommendations are to include environmental and human factor impacts.

3. A review and analysis of projected benefits will be made. Data will document salient factors impacting on these projections and suggest whether projections should be expanded or contracted. Also, data are expected to determine whether additional factors not previously considered impact on current projections.

4. Comparisons will be made of the work distribution before and after implementation of the Laboratory Operations Center (LOC) model for verfication of real benefits with projected benefits.

It should be noted that the LOC is not completely installed and the total capabilities and impact of the system cannot be evaluated. It is projected

that item four (4) above will be addressed during subsequent research.

IV. THE HUMAN RESOURCES LABORATORY MANAGEMENT MODEL

The Air Force Human Resources Laboratory at Brooks Air Force Base in San Antonio, Texas, has been selected by the Air Force to develop a prototype Laboratory Operations Center (LOC). It has been envisioned that the technique and procedures for the LOC will be applied to operation centers soon to be developed in other Air Force laboratories.

The purpose of the Laboratory Operations Center (LOC) is to design, develop, implement and operate Management Information System (MIS) services for personnel of the AFHRL. Specific functions are:

a. Define the management process in terms of information sources and flows, decision-making methods, evaluation criterion, and program progress monitoring.

b. Advise the Commander and other principal managers on use and implications of MIS applications.

c. Create a data administration environment and define roles and responsibilities of participants.

d. Develop a prototype for an AFSC Operations Center.

e. Direct the AFHRL participation in the AFSC Command Acquisition of Scientific Environments (CASE).

f. Provide support for ADP staffing functions of AFHRL.

g. Maintain certain existing MASIS, JOCAS, JAMIS, etc.

h. Support the AFSC CMIS effort with management and technical representation.

A Special Project Office is being used to support the LOC development. The planned installation of the data processing computer, combined with text-editing features on an experimental basis, is part of Project IMPACT; as such, the installation can contribute to the body of data being collected to demonstrate the costs and benefits of office automation at various locations within the Air Force Systems Command.

The measurement of costs and benefits of the systems at AFHRL will make use of the data and analytic techniques developed in Project IMPACT. Such further use and lessons learned from the detailed investigation of procurement and control procedures, will be of value to AFSC during subsequent employment of IMPACT methods.

Office automation systems of the type employed at AFHRL are a combination of word processing and data processing. Successful operation of such systems requires the preparation of complex application programs for the computer portion of the system. The IMPACT technique for data collection and analysis, which involves the study and charting of office operations, can provide data and guidance for programming system design at AFHRL.

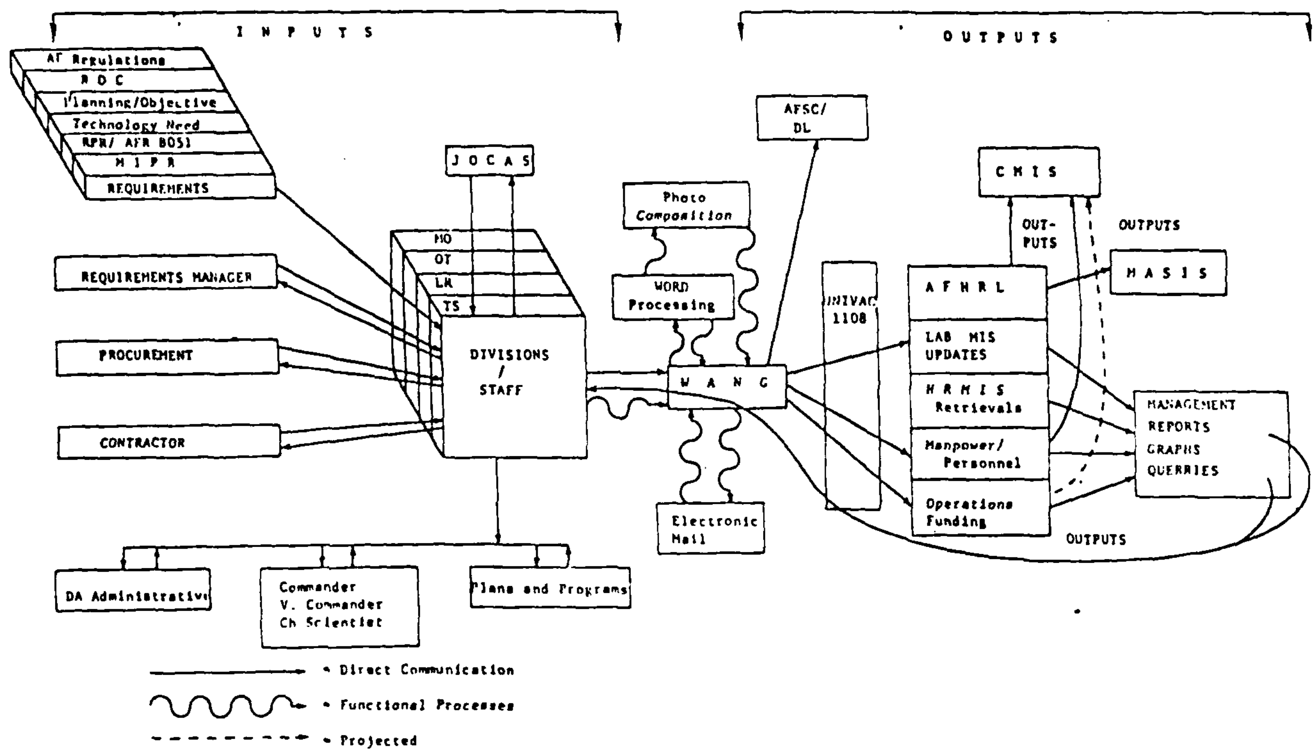
The LOC is serving as a pilot development for the Command Operations Center. The laboratories are working to develop a single common-wide reporting system. (See Figure IV 1). Figure IV-1 represents a composite word processing/data entry flow of the Management Information System at AFHRL. As can be shown on Figure IV-2, information is output to HQ AFSC/DL, Command Management Information Systems. AFHRL needs lab MIS updates, manpower and personnel, and operations fundings. From these services are produced management reports, graphs, queries, and MASIS.

The information system is designed to serve all four divisions in the AFHRL, together with the staff, including the Administrative Office, Commander/Vice Commander, Chief Scientist and Plans and Programs Office. As noted in Figure IV-1, Requirements, the requirements manager, procurement and contractor interface with the divisions. Here, information is processed though Wang processor to Univac 1108.

Data processing equipment at HRL represents the latest state-of-the-art capabilities in graphics and usual display devices. Equipment includes a large-screen and projected back-lit display device, a color graphic keyboard display terminal with storage and memory capabilities, and a hard copy device. The equipment provides for generating charts and graphs given the data parameters. At present, data goes through the terminal to a 6500 Xerox machine which makes a transparency which can be projected.

Given the mission of AFHRL and the unique organizational structure, an efficient and highly productive management system must address both the differentiation and integration components for optimal results. Differentiation responds to the need for minimizing duplication of effort, and several interviewees suggested duplication of reports and efforts required some attention at HRL. The diverse organizational objectives, together with a prolific research capability, encumbers the laboratory to focus on the integration factor. This type of management system makes possible the results

FIGURE IV-2 THE AIR FORCE HUMAN RESOURCES LABORATORY WORD PROCESSING / DATA ENTRY FLOW CHART



of different projects to be combined for the achievement of organizational objectives.

It has been suggested that a laboratory newsletter outlining the long range objectives and the laboratory's progress toward these objectives be used. A video taping or newsletter of division level developments would promote interdivisional communication, and periodic meetings of research teams to discuss progress, efforts, and problems the research scientist level might be employed. Other communication needs include the need to know who should receive what type of information as well as the frequency of this information.

From the duplicity stance, interviewees suggested that information needs for AF Forms 11, 22, 23, 25, and 37 be combined and automated.

Researchers and administrators think that documents requiring periodic update (monthly, weekly, quarterly) might best be automated. A tracking system for division and branch chief expenditures could be targets for computerization. The several categories of expenditure (budget items) which have been computed by hand might be considered for automation. This has been suggested for the entire Laboratory. Also suggested for automation was the Airman's Performance Rating (APR) and all written communications which are scheduled, systematized or standard. Others suggested need for a tracking system showing status on monthly/quarterly reports. Communicative needs have suggested indicating action of initiated, committed or obligated.

Information needs included the need for Headquarters to have strategic planning schedules, (or thrust schedules) and schedule variance, Division demand and forecast; marketing strategy, projected budgets, operating plans, research project summaries, manpower status; resource requisitions, fiscal year budgets and expenditures, and schedules for research performance which includes dates for project deliverables.

Further, Division level needs include knowledge of counterparts action. Information could include summaries of division's thrust schedules, and research emphasis, (basic, exploratory, or advanced development). Such information might be broken out by fiscal year dollar expenditures, in-house versus contract research and the organizations that are the customers for that

Division's products.

Division Chiefs and their respective staff should receive information related to outstanding work unit variance, a list of scheduled deliverable within specified time periods, identification of projects that are experiencing cost overruns or cost underruns, equipment purchase summaries, narratives of division work units and market analysis.

Other areas of information needs for the entire Laboratory consisted of systems for updating personnel files, telephone listings, deadlines for action, all budgetary items, training functions and action items. All accounting functions, policy specifying, development, analysis, and revisions and maximizing benefits/costs and determining payoff of utilities. It was also suggested that a system for evaluating the value of information systems be introduced. The capabilities of the system should be evaluated.

Branch Chiefs should receive information including outstanding cost and/or schedule variance for each work unit in the Branch; summary descriptions of each work unit, long monthly progress statements, cash flow variance reports, branch manpower status reports, work completed reports, and market analyses.

In a report entitled, "A Comparison of a Theoretical Laboratory MIS Design with an Existing Laboratory System," Lieutenants Tom Martin and Lynn M. Scott stated the following:

"Interagency information needs can be satisfied by providing two forms of information packages. Package #1 consists of budgeting - (both fiscal expenditures and projections), schedules of performance and an assessment of the thrust plans. Systems Command Headquarters would be the recipients of this plan. Package #2 would consist of thrust plan and work unit summaries. This package would be sent to other Air Force agencies and Department of Defense agencies. These two information packages, in total, provide information of new developments and/or progress in existing efforts thus linking AFHRL with the external environment." This report was prepared at the AFHRL.

Persons interviewed also felt that the Laboratory could profit by administering the occupational task Inventory Survey and the Occupational

Attitudinal/Assessment Inventory Survey to personnel employed at HRL. Also, they suggested an introductory program for incoming scientists which would be computerized. A criteria for prospective automated tasks together with a productivity criteria might be developed.

Perceptions of interviewees were unanimous in voicing support for management's effort to improve the information process. Particularly were they pleased with the idea of consulting with administrators and scientists concerning the best course of action to pursue in making these advancements.

V. RECOMMENDATIONS

Documents, records and interviews indicate that AFHRL is not only committed to and interested in management improvement, but also, that positive steps are being taken to update and advance a quality, effective management information system. A cost benefit analysis study of the LOC seems to be a logical candidate for contemplation. Pursuant to review of the Booz-Allen proposal, it is suggested that this proposal be excogitated. Validation of base line data, determining base line productivity, specifying operational systems requirements in quantitative terms, and performing post implementation audits of office automation systems might also be pondered and reviewed.

There is a need to know more about how the LOC affects the duties of the task scientists, and to know more about these duties together with the exact limits of the new system's capability. Also, what is needed is to educate the personnel at HRL regarding the system and how it proposes to enhance their working environment. Management needs to know the cost effectiveness of the LOC and continued study should be made in this area. (See Comptroller General's recommendation, this paper).

A second area of study would include the administering of both the Occupational Task Inventory Survey and the Occupational Assessment Inventory Survey to HRL employees. These surveys are designed to show in greater detail just what individuals actually do, the importance of the task, what is required for acceptance and how employees' background and other factors may impact on their relative success in the organizaion. This I propose to do over the next one and one half years. This study also meets the Comptroller General's recommendation in 1979 to "plan studies of the new systems effect on personnel."

It is also recommended that a model for predicting productivity trends of the HRL be completed. This I propose to do with the mini-grant as follow-up to this study.

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FINAL REPORT

INFLUENCE OF REACTION VARIABLES ON THE ELECTRICAL PROPERTIES OF HOMOEPITAXIAL InP IN THE HYDRIDE SYSTEM

Prepared by:	Dr. Tim Anderson
Academic Rank:	Assistant Professor
Department and University:	Department of Chemical Engineering University of Florida
Research Location:	Rome Air Development Center/ESM/Hanscom AFB
USAF Research Colleague:	John K. Kennedy
Date:	September 18, 1980
Contract No:	F49620-79-C-0038

INFLUENCE OF REACTION VARIABLES ON THE ELECTRICAL PROPERTIES OF HOMOEPITAXIAL InP IN THE HYDRIDE SYSTEM

by

Tim Anderson

ABSTRACT

The effect of various reaction variables on the unintentional doping levels in homoepitaxial InP were investigated in the hydride system. The predominant impurity was believed to be Si produced through interaction of HCl with the quartz reaction tube and reaction parameters reported important in GaAs deposition and the chloride process were examined. The H_2 flow rate in the PH_3 inlet tube and both the PH_3 and HCl inlets was varied and produced no sizeable effect on the 77°K free carrier concentration and mobility as measured with the Van der Pauw technique. An independent HCl sidestream was introduced to the process and resulted in minor changes in the electrical properties and yielded a decrease in growth rate with increasing HCl flow. The temperature in the mixing zone was varied thus changing the PH_3 decomposition extent and again produced a negligible change in the measured electrical properties. Procedures were established for InP substrate preparation and reaction conditions were found that reproducibly yielded device quality InP films with free carrier concentrations near $10^{15} cm^{-3}$.

ACKNOWLEDGEMENT

I am obliged to the Air Force Systems Command, the Air Force Office of Scientific Research and the Southeastern Center for Electrical Engineering Education for providing the opportunity to participate in the excellent research efforts at the Rome Air Development Center, Hanscom AFB, Mass. Recognition is deserving to the Solid State Science Division and in particular to the EM Materials Technology Branch.

John Kennedy deserves special thanks, whose support and guidance is credited with making this project an invaluable experience for myself. Appreciation is given to Bill Potter for his knowledgeable assistance in making ideas a reality. Finally, I would like to thank Eirug Davies, Joe Lorenzo, Joe Weiner and Hank DeAngelis for their many helpful discussions.

I. INTRODUCTION

The past 25 years have witnessed the emergence of a major industry based upon the semiconductor material, Silicon. The technology surrounding Si has resulted in tremendous progress in such diverse areas as computation, process control and communications, and has penetrated several aspects of our everyday life. Unfortunately, Si has only one set of physical and electrical properties upon which to design solid state electronic devices. Thus the search for new semiconductor materials has proceeded and a major class of semiconductor materials, III-V compounds and solutions, are currently receiving intense investigation for use in solid state devices. These materials offer several advantages over Si and include improved electrical properties (electron mobilities can be more than two orders of magnitude larger resulting in "faster" devices) as well as showing miscible solutions on both the Group III and Group V sub-lattices (this allows for 2 degrees of freedom in property selection, as for example bandgap energy and lattice parameter). This last point is illustrated in Figure 1 in which the lattice parameter is plotted against bandgap energy. In this figure a point represents a binary compound, a line represents a ternary solid solution, and an enclosed area depicts substitution on both sub-lattices (quaternary solid solution). The binary compounds with asterisks indicate that the material is available in bulk single crystal form and thus useful as a substrate material. In opto-electronic applications, the design problem is to specify both the bandgap energy, insuring the desired optical properties, and the lattice parameter, providing lattice matching. As an example, the $In_xGa_{1-x}As_yP_{1-y}$ solid solution can be lattice matched to InP so as to allow a wide range of bandgap energies that include the 1.3μ wavelength important for optical communication devices.

There are three primary techniques for growing III-V epitaxial films and include molecular beam epitaxy (MBE), liquid phase epitaxy (LPE) and vapor phase epitaxy (VPE). Of these growth methods, VPE is the most promising from a large scale production viewpoint and is currently used in Si technology. In VPE a vapor specie(s) is used to transport the desired epitaxial film elements to the substrate location at which point the solid semiconductor material is formed by an appropriate change in temperature. As indicated above, it is of interest to deposit a film consisting of the 4 elements In, Ga, As and P and an understanding of this complicated process

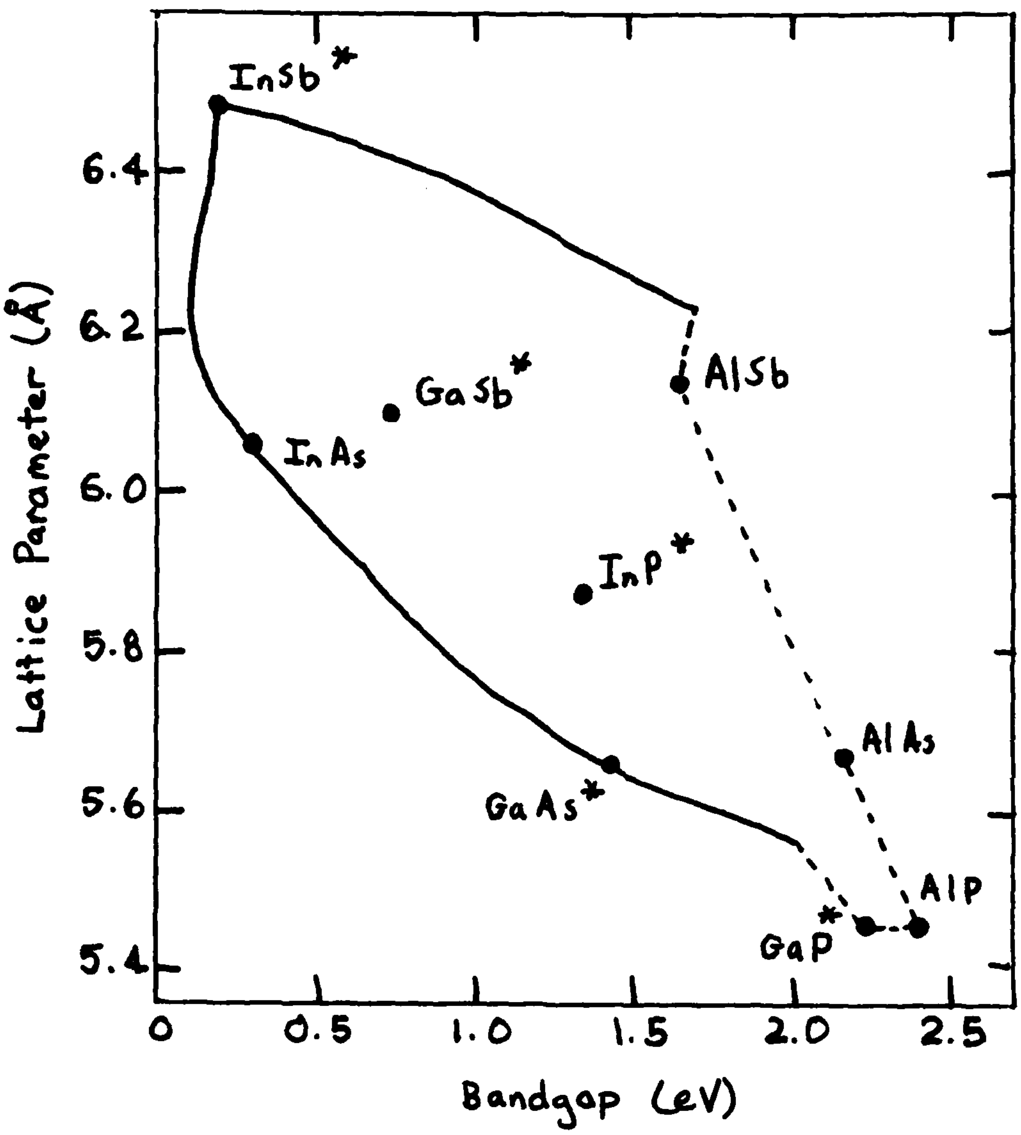

Figure 1. Latice parameter versus bandgap energy in Group III-V semiconductors.

will only be gained through knowledge of the simpler binary deposition systems. The work detailed here is concerned with the homoepitaxy of the binary In-P system. Previous VPE deposition processes have transported In as a chloride or organometallic and P as a chloride or hydride. The particular vapor species chosen here are the In chloride and the P hydride as this selection allows one to independently vary both the Group III and Group V amounts (extremely important for deposition of the quaternary) and avoids safety and impurity problems associated with organometallics. This particular system is termed the hydride process as phosphorous is injected into the reactor as PH_3 as opposed to the chloride process which inputs PCl_3.

Generally it is required that a process reproducibly yield layers of low unintentional doping levels while the desired doping levels are achieved by the controlled addition of electrically active impurities. This report describes work aimed at elucidating the reaction variables which control the unintentional doping levels in epitaxial InP and parallels similar studies performed with GaAs and InP in the chloride process.

II. OBJECTIVES

The principal objective of this effort was to examine the homoepitaxial deposition of InP in an existing hydride vapor phase reactor. Previous work at the laboratory had extensively characterized the hydride deposition of the binary compound GaAs and resulted in the ability to produce high purity[1] epitaxial layers with excellent morphology.[2] By changing various reactor variables such as temperature profiles and reactant flow rates, very precise variations of both the unintentional doping level and surface morphology could be produced and thus utilized to reproducibly grow device quality epitaxial layers of GaAs. With the long range goal of having a similar ability to produce excellent epitaxial layers of $Ga_xIn_{1-x}As_yP_{1-y}$, one must first have an understanding of the deposition process in the quaternary limit $x \rightarrow 0$ and $y \rightarrow 0$, InP. The objectives of this work are thus directed at InP deposition and are two-fold.

(1) Define a procedure for obtaining acceptable surface morphology reproducibly in the hydride system for the deposition of InP and entails examining both the substrate preparation procedure and the conditions of deposition.

(2) Ascertain the mechanism(s) that control the unintentional doping levels in epitaxial InP. The remainder of this report describes the approaches taken to satisfy these objectives and discusses their results.

III. SUBSTRATE PREPARATION AND SURFACE MORPHOLOGY

The proper preparation of the substrate (Fe-doped semi-insulating InP) is of critical importance as the resulting epitaxial layer can be of no higher quality than the starting substrate. Based upon previous work with the Ga-As system, InP single crystal wafers were sliced (approximately 20 mils in thickness) from a LEC grown InP boule and oriented 2° off the (100) plane in the [111] direction. Initially these wafers were mechano-chemical polished using a rotating Pellon part and a 1% Br/Methanol solution, removing approximately 2 mils of surface. This technique yielded substrates that exhibited a severe orange peel appearance and almost ridge-like in nature as exemplified in Figure 2a. This effect can be eliminated[3] by using isopropanol as the Br solvent instead of methanol, presumably due to the increased solution viscosity. In addition, the polishing solution was chilled to ~ 5°C before use and resulted in an increased lifetime of the solution (approximately 30 minutes as the etching ability decreased due to Br reaction with the alcohol) and further increased the solution viscosity. The substrates were attached to a quartz mounting block with black wax and removed with TCE. The etchant was removed from the polished InP slice by spraying with isopropanol and methanol and immediately blown dry to prevent evaporation marks. An example of the polished surface thus produced is depicted in Figure 2b.

Following the polishing step the InP slice was diced into smaller slices (approximately 1 cm^2) that were of an appropriate area for the reactor. Just prior to inserting the substrate into the reactor the following preparation procedure was developed. Degreasing of the substrate was accomplished by a series of washes in an ultrasonic

Figure 2a. Br/Methanol polish.

Figure 2b. Chilled Br/Propanol polish.

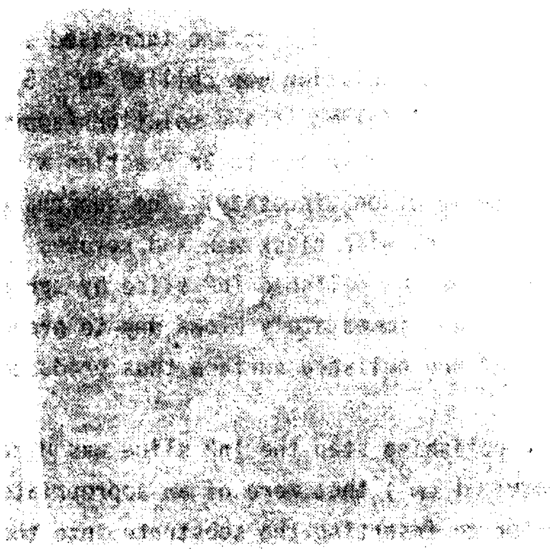

Figure 2c. Substrate prior to deposition.

cleaner and included TCE, toluene, acetone and methanol sequentially. After degreasing the slice was etched in Caro's acid (5:1:1, H_2SO_4:H_2O_2:H_2O) for 5 minutes and removed any oxide (indium sesquioxide) present on the surface while only etching InP minimally.[3] After rinsing with deionized water the substrate was next etched in a fresh 0.3% Br/methanol solution for 2 minutes in a tilted (45°) and rotating (1-2 R.P.M.) beaker and thus insured a reproducible etch. The next step consisted of rinsing with methanol, followed by another 5 minute Caro's acid etch, and a D.I. water rinse. Finally, the etched substrate was rinsed in methanol and blown dry with He before insertion into the epitaxial reactor. It was found important to perform these steps just prior to deposition in order to achieve good surface morphology. Though a considerable number of substrate preparation techniques exist in the literature, this procedure proved to provide the best substrates. Other substrate preparation methods were examined and included variations of the Br/methanol concentration and etch time, iodic acid/water solutions, 1% HBr/water and concentrated nitric acid or 45% KOH/H_2O in place of the Caro's acid. An example of a typical substrate prior to deposition is shown in Figure 2c.

Shown in Figure 3 is a schematic of the experimental reactor used for depositing InP in the hydride system and is similar to the apparatus described by Tietjen and Amick.[7] Briefly, the physical process occurring is the following. The Group III source, in this case In, is generated by passing HCl diluted with H_2 over a boat of liquid In metal with the following reaction occurring

$$x\mathrm{In} + \mathrm{HCl} \rightleftarrows x\mathrm{InCl} + (1-x)\mathrm{HCl} + \frac{1}{2}x\mathrm{H_2} \qquad (1)$$

where x denotes the fraction of HCl which reacts with the In. This gas mixture of InCl (with a small amount of $InCl_3$), H_2 and HCl is mixed in the center zone with a PH_3 and H_2 stream that enters the reactor via a 1/4" O.D. inner inlet tube. Primarily in this region phosphine decomposition occurs according to

$$\mathrm{PH_3} \rightleftarrows (1-y)\mathrm{PH_3} + (1-\alpha)(y/4)\mathrm{P_4} + \alpha(y/2)\mathrm{P_2} + \frac{3}{2}y\mathrm{H_2} \qquad (2)$$

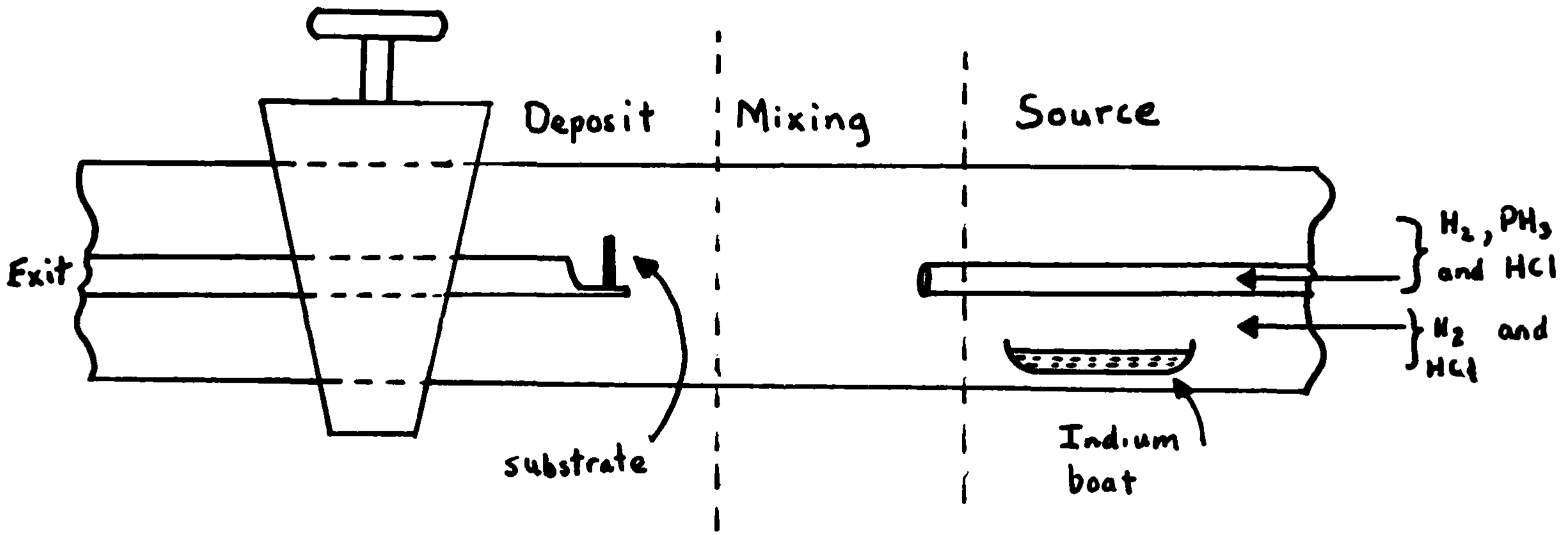

Figure 3. Schematic of the epitaxial reactor.

Here y is the fraction of phosphine decomposed and α is the degree of dissociation of P_4 into the dimer. This reaction mixture is transported to the deposition zone which contains the substrate. Reactants are transferred from the bulk gas phase across a semi-stagnant boundary layer to the substrate where deposition of InP proceeds as

$$InCl + (1-\beta-\gamma)PH_3 + \frac{1}{2}\beta P_2 + \frac{1}{4}\gamma P_4 \rightleftarrows InP + HCl + [1-\frac{3}{2}(\beta-\gamma)]H_2 \quad (3)$$

In this reaction β is the fraction of InCl which reacts with P_2, γ the fraction with P_4 and $(1-\beta-\gamma)$ the fraction with PH_3. Finally, the product gases are transferred across the boundary layer and transported to the reactor exit. Further experimental details are described by Kennedy et al.[1,2]

At the disposal of the operator then are control of the following reactor conditions: temperatures in the source, center and deposition zones and mass flows of PH_3, HCl and the H_2 carrier at both entrances. Based upon previous experience in the laboratory and the existing literature, the temperatures were fixed to be T_{source} = 900°C, T_{center} = 950°C and $T_{deposit}$ = 650°C. The remaining flow rate variables were examined with the objective of obtaining a quality surface morphology. Acceptable, though not optimized, surface quality was obtained with the following volumetric flows: PH_3 = 3.3 sccm, H_2 (PH_3 carrier) = 1220 sccm, HCl = 4.8 sccm and H_2 (HCl carrier) = 1220 sccm. The morphology was found to be most sensitive to the V/III ratio and the apparent ratio here is 0.7 and a factor of 2 higher than used in the chloride system deposition of InP.[8,9] However, the important parameter is the actual V/III ratio in the vicinity of the substrate surface and will be different than the inlet ratio due to incomplete reaction of HCl with In in the source region. According to the mass spectrometric studies of Ban,[10] at 900°C only 82% of the HCl will react with the In metal and will further raise the V/III ratio (to .84). In addition to the mass transfer limitation of the source reaction, the phosphine decomposition is similarly limited. Ban found that an initial mixture of PH_3 and H_2 with $P_{PH_3} = 1.6 \times 10^{-2}$ atm will decompose to an extent of 75% at 650°C (deposition temperature) and ~93% at 950°C (center temperature), with approximately twice the amount

of dimer as tetramer (reported only at 850°C). In the chloride system the thermodynamic calculations of Shaw[12] indicate that the tetramer should be the dominant phosphorous specie in the vapor phase. Additionally, the work of Born and Robertson[13] and Fairhurst et al.[14] propose that PH_3 is considerably more efficient in reacting with InCl than either P_4 or P_2 (in contrast with GaCl; $As_4 > As_2 \approx AsH_3 \approx P_4 > P_2 > PH_3$[11]). From these observations it can be concluded that a comparison of inlet V/III ratios between the two deposition systems is not absolute as the P distribution among PH_3, P_4 and P_2 differs as does the reactivities of these species with InCl. A comparison with epitaxial Ga-As finds a V/III ratio of 0.54 in the chloride process and near 1.8 for the hydride method.[2] Though the ratio of these two numbers is higher for the deposition of GaAs, they can be realigned by accounting for the increased observed decomposition of AsH_3 vs. PH_3, the smaller diffusivity of the arsenides versus phosphorous compounds and the increased efficiency of HCl reaction with Ga. Thus the results found are partially consistent with previous work though kinetic limitations produce distinct differences in the chemistry among both processes and systems (from an equilibrium viewpoint identical chemistry should be evident).

IV. THE EFFECT OF THE HYDROGEN CARRIER GAS FLOW RATE ON THE ELECTRICAL PROPERTIES OF EPITAXIAL InP

The unintentional doping of vapor phase epitaxial InP is believed to be due to Si incorporation and generated by reduction of the quartz reactor walls with unreacted HCl.[15,16] The model proposed consists of a chlorosilane generation step

$$nHCl + SiO_2 + (4-n)H_2 \rightleftarrows SiCl_nH_{4-n} + 2H_2O \qquad (4)$$

followed by mass transport to the substrate. Next, the Si is incorporated into the growing interface according to the reaction sequence

$$SiCl_nH_{4-n} + (n-2)H_2 = Si_{ad} + nHCl \qquad (5)$$

$$Si_{ad} + V_{In} \rightleftarrows Si_{In} \qquad (6)$$

and

$$Si_{In} \rightleftarrows Si_{In}^{+} + e^{1} \qquad (7)$$

This incorporation mechanism thus will yield the InP n-type and results in a carrier concentration of

$$n = \left[\frac{[V_{In}]\, P_{H_2}^{n-1}\, P_{SiCl_nH_{4-n}}}{P_{HCl}^{n}} K_5K_6K_7\right]^{1/2} \tag{8}$$

In arriving at this expression it was assumed that the InP growth is highly extrinsic and thus the electroneutrality condition stipulates $n \cong [Si_{In}^{+}]$. The indium vacancy concentration can be expressed in terms of the surface gas phase composition by examining the following defect reactions

$$InP \rightleftarrows In_{ad} + V_{In} + P_{ad} + V_p \tag{9}$$

$$HCl + In_{ad} \rightleftarrows InCl + \frac{1}{2} H_2 \tag{10}$$

and results in a carrier concentration of

$$n = \left[\frac{P_{H_2}^{n-3/2}\, P_{SiCl_nH_{4-n}}}{P_{HCl}^{n}\, P_{InCl}\, a_{P_{ad}}[V_p]} K_5K_6K_7K_9K_{10}\right]^{1/2} \tag{11}$$

if the activity of InP is assumed to be unity. As the chlorosilane pressure is determined upstream of the substrate and the reactor is flooded with H_2 carrier gas (resulting in a relatively constant partial pressure), the carrier concentration according to this mechanism would be primarily determined by the partial pressures of HCl ($\alpha\ P_{HCl}^{-(n-1)/2}$, n=1,2,3,4) and InCl ($\alpha\ P_{InCl}^{-1/2}$) and the square root of the 1/P ad-atom activity ($\alpha\ P_{P_2}^{-1/2}$, $\alpha\ P_4^{-1/4}$, $\alpha\ P_{H_2}^{3/2}/P_{PH_3}$). In a manner following that of Kennedy et al.[1] the H_2 carrier gas flow rate was varied in hopes of establishing conditions of very low carrier concentrations. Thus a decrease in the H_2 content should, holding the amounts of the remaining specie constant, produce a proportional increase in their partial pressures and result in a net decrease in the free carrier concentration (for example dropping the H_2 flow rate in half should change n approximately by $[2(2)^{n-1}\ (\sqrt{2}, \sqrt{2}, 2)]^{1/2} = 1.7$ to 5.7 depending

upon the value of n and the important phosphide species). Corresponding to the decrease in free carrier concentration, an increase in the carrier mobility should be observed as the density of scattering centers has decreased.

In order to investigate this proposed mechanism the H_2 carrier flow associated with the PH_3 inner inlet tube was varied and the free carrier concentration and mobility were measured by the Van der Pauw method.[17] In these measurements ohmic contacts were made by contacting phosphorous doped Sn to a 135 mil square layer in the presence of ~ 0.3% HCl/H_2. The H_2 flow was varied only in the PH_3 inner tube in order to insure the extent of reaction of HCl with the liquid In remained constant. In addition to increasing the reactant mole fractions, the decrease in H_2 carrier flow might also alter any kinetically limited processes in the center zone of the reactor as the residence time would decrease (such as the extent of phosphine decomposition or the HCl interaction with the quartz reactor walls). The results of these experiments are shown in Figures 4 and 5 in which the free carrier concentration and mobility are depicted at 300K and 77K, respectively. The results indicate an apparent maximum in the carrier concentration and a minimum in the observed mobility and is not consistent with the model proposed in the literature. The experimental error associated with the mobility measurement is smaller than the free carrier concentration error since the mobility is independent of the layer thickness. With this in mind, the apparent minimum may be due simply to scatter in the measurements.

The recent work of Zinkiewicz et al.[18] indicates that the growth rate decreases rather sharply as the H_2 flow rate decreases for constant HCl and PH_3 inlet flow rates, indicating a mass transport limited growth mechanism. The results of this work showed no substantial change in the growth rate as the H_2 flow was varied, and if any trend existed it was towards an increase in growth rate as the H_2 flow rate decreased, suggesting a diffusion controlled mass transfer mechanism.

By varying the H_2 carrier flow associated with the PH_3 inlet only, a small change in $P_{PH_3}^{inlet}$ (1.2×10^{-3} to 2.6×10^{-3}) could be introduced due to the screening effect of the large H_2 flow rate over the In boat. Thus a second set of experiments were performed in which the H_2 carrier flow rate

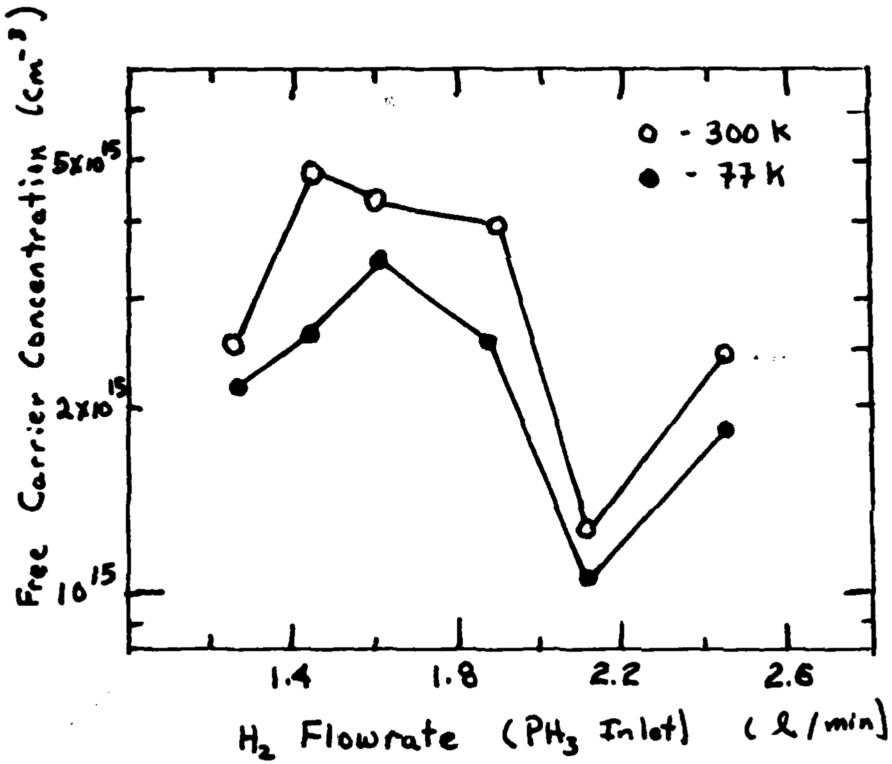

Figure 4. Free carrier concentration versus H_2 flowrate (varied in PH_3 inlet).

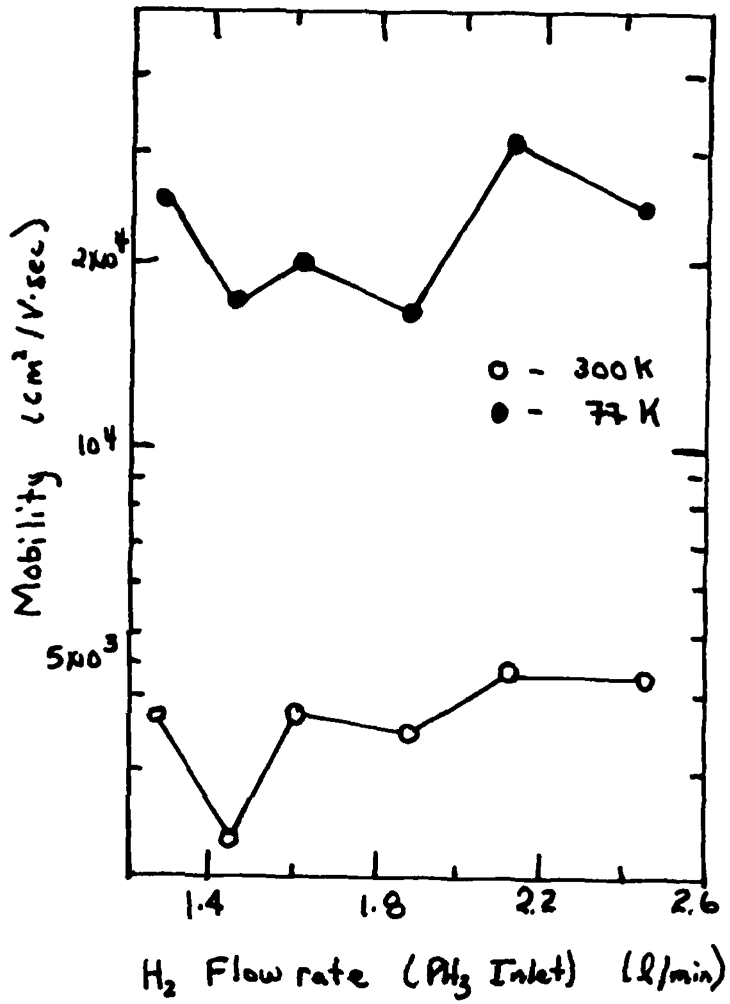

Figure 5. Electron mobility versus H_2 flowrate (varied in PH_3 inlet).

was varied evenly in both the PH_3 and HCl inlets. The results of the electrical measurements are displayed in Figures 6 and 7. It can be seen that again no significant variation in the free carrier concentration or mobility is apparent and in sharp contrast to similar studies with Ga-As.[1] Again, the growth rate showed a slight increase with decreasing H_2 carrier flow rate. Thus, in contrast to other reported results for both InP and GaAs deposition with the hydride technique no appreciable effect of the H_2 carrier flow rate could be found on either the growth rate or impurity incorporation extent.

V. EFFECT OF HCl FLOW RATE ON THE GROWTH RATE AND ELECTRICAL PROPERTIES OF VPE InP

An additional HCl flow was introduced with the PH_3 flow in order to examine if the carrier concentration would decrease as predicted by Equation (11). The HCl was introduced with the PH_3 in order to hold the amount of InCl constant and should only change the concentration of chlorosilanes in the eventual gas phase composition in the substrate vicinity. The growth rate should also show a decrease as the HCl content increases as can be easily ascertained from Reaction (1). The results of the electrical measurements are shown in Figures 8 and 9 and again show an apparent minimum in the free carrier concentration and a maximum in the electron mobility, though the observed effect is contrary to that expected and possibly due to experimental error.

Figure 10 displays the observed growth rate as measured by a weight change for various flow rates of HCl. The growth rate remains constant until an external flow rate of 1 cc/min HCl is reached and then begins to fall, reaching a zero growth region near 1.8 cc/min HCl. The ability to etch InP in situ with HCl might prove to be useful in the substrate preparation procedure, though the samples etched for 45 minutes contained large etch pits.

VI. EFFECT OF CENTER ZONE TEMPERATURE ON THE ELECTRICAL PROPERTIES OF VPE InP

From the expression for the free carrier concentration as determined by Si incorporation via chlorosilanes, it can be seen to be inversely proportional to the phosphorous ad-atom concentration. Pogge and Kemlage[19]

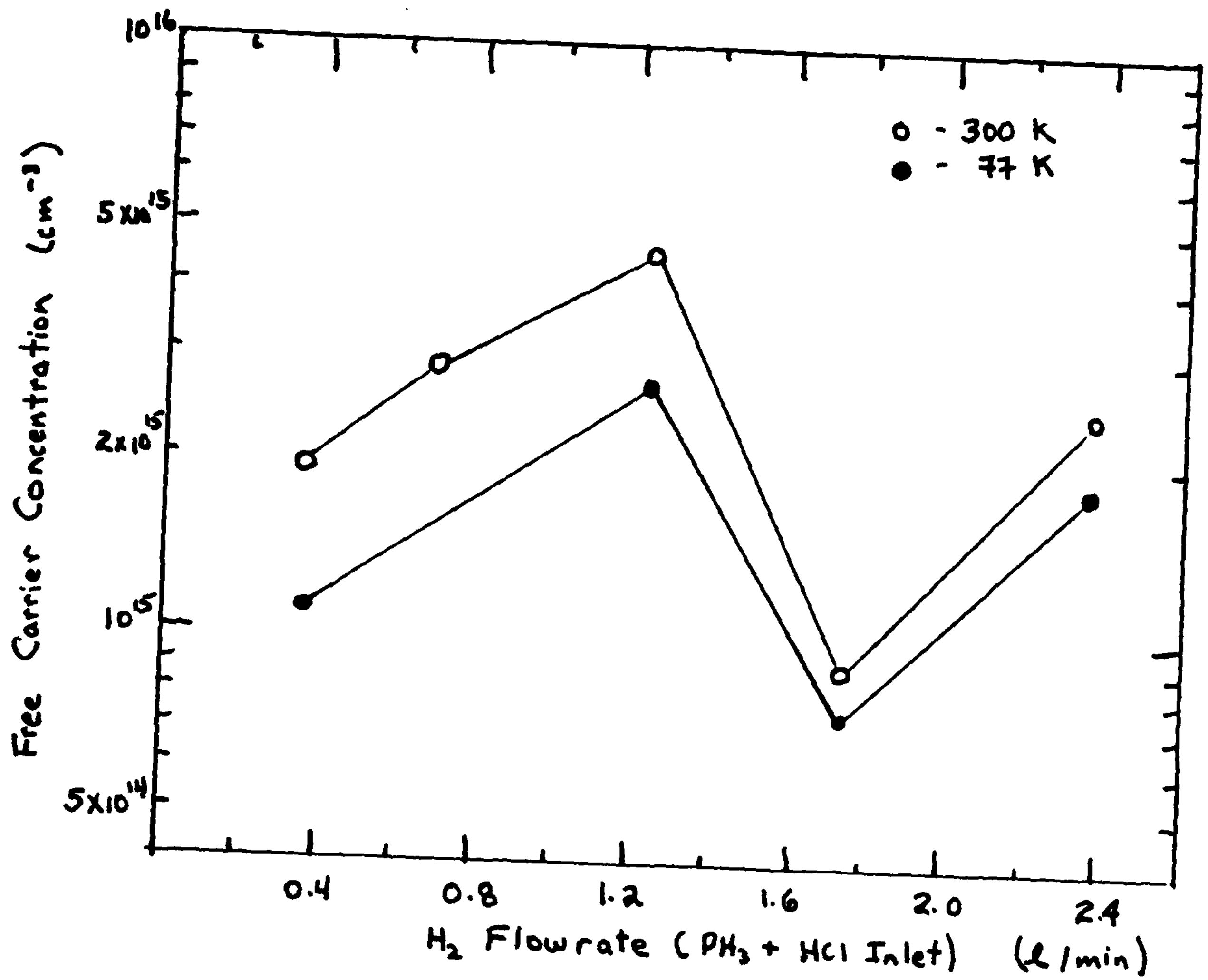

Figure 6. Free carrier concentration versus H_2 flowrate (varied in both inlets).

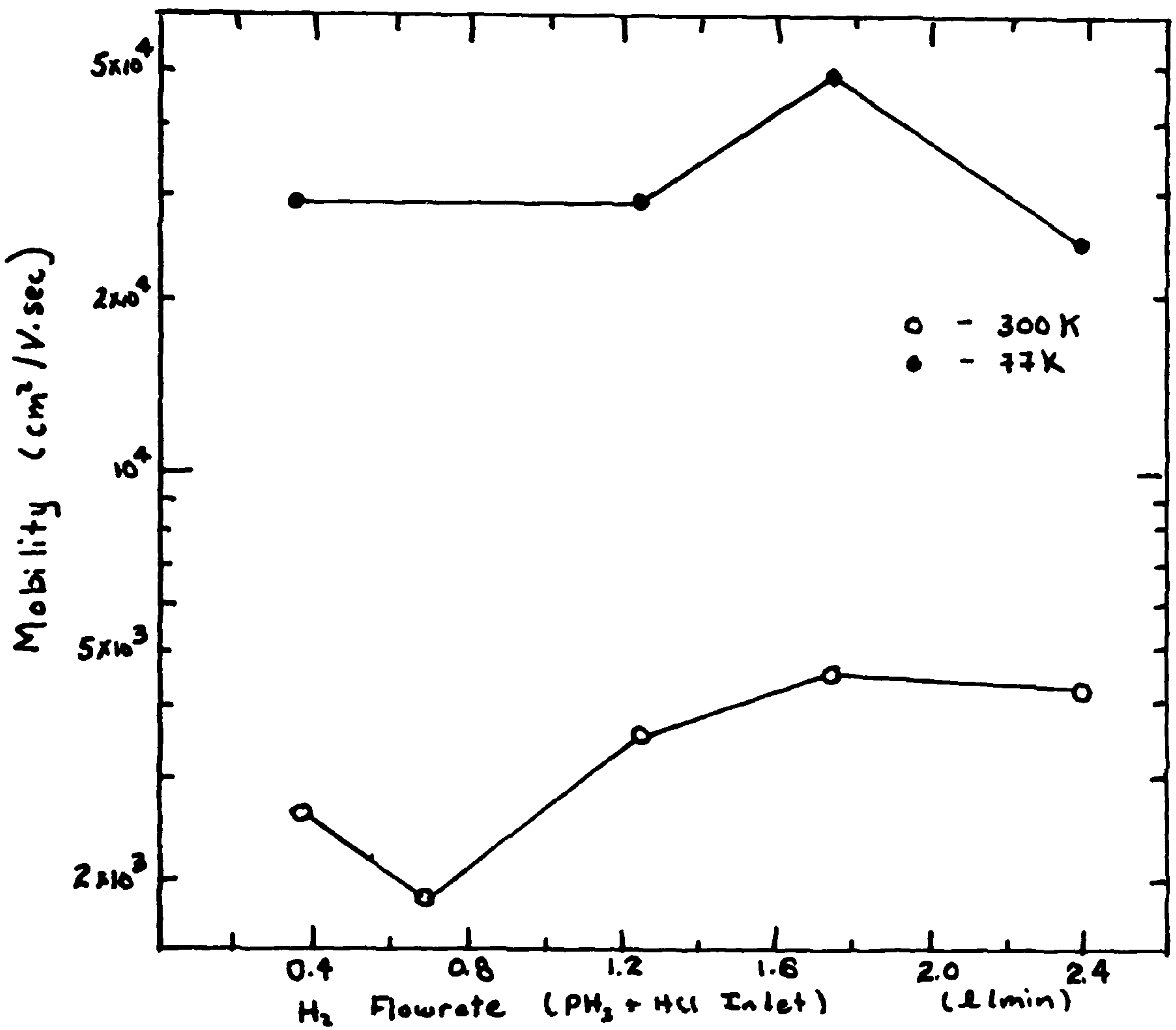

Figure 7. Electron mobility versus H_2 flowrate (varied in both inlets).

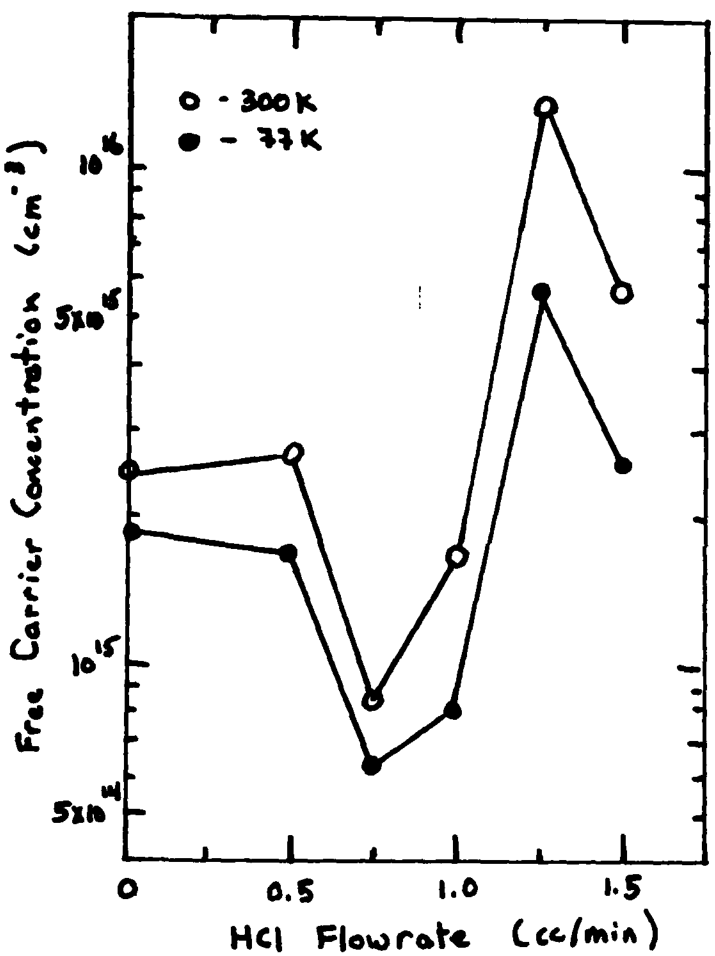

Figure 8. Free carrier concentration versus sidestream HCl flowrate.

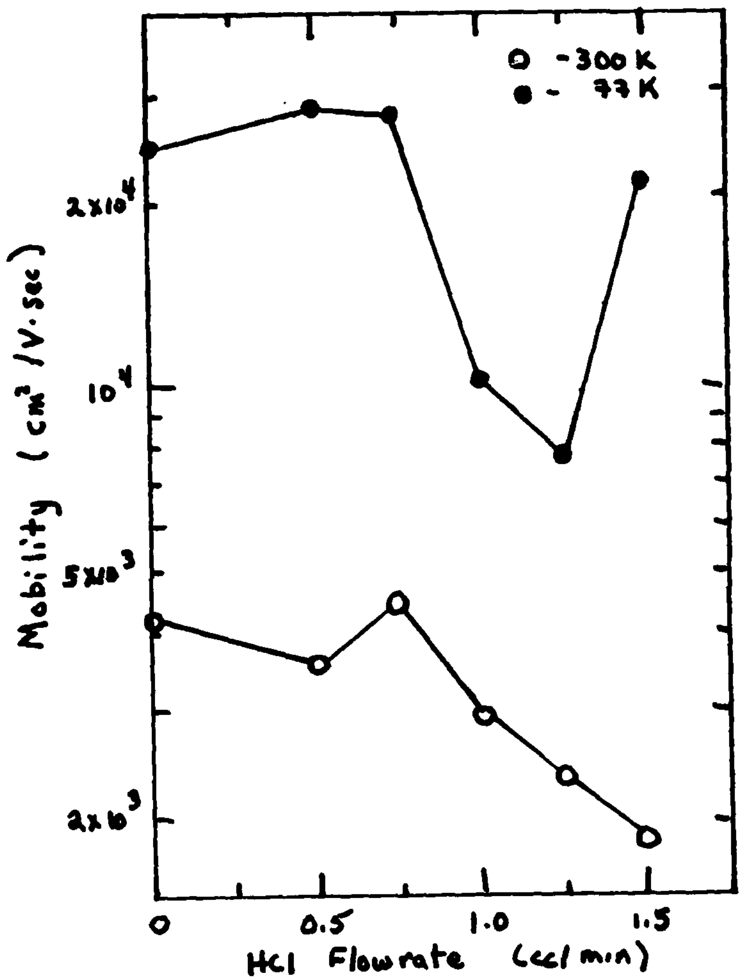

Figure 9. Electron mobility versus sidestream HCl flowrate.

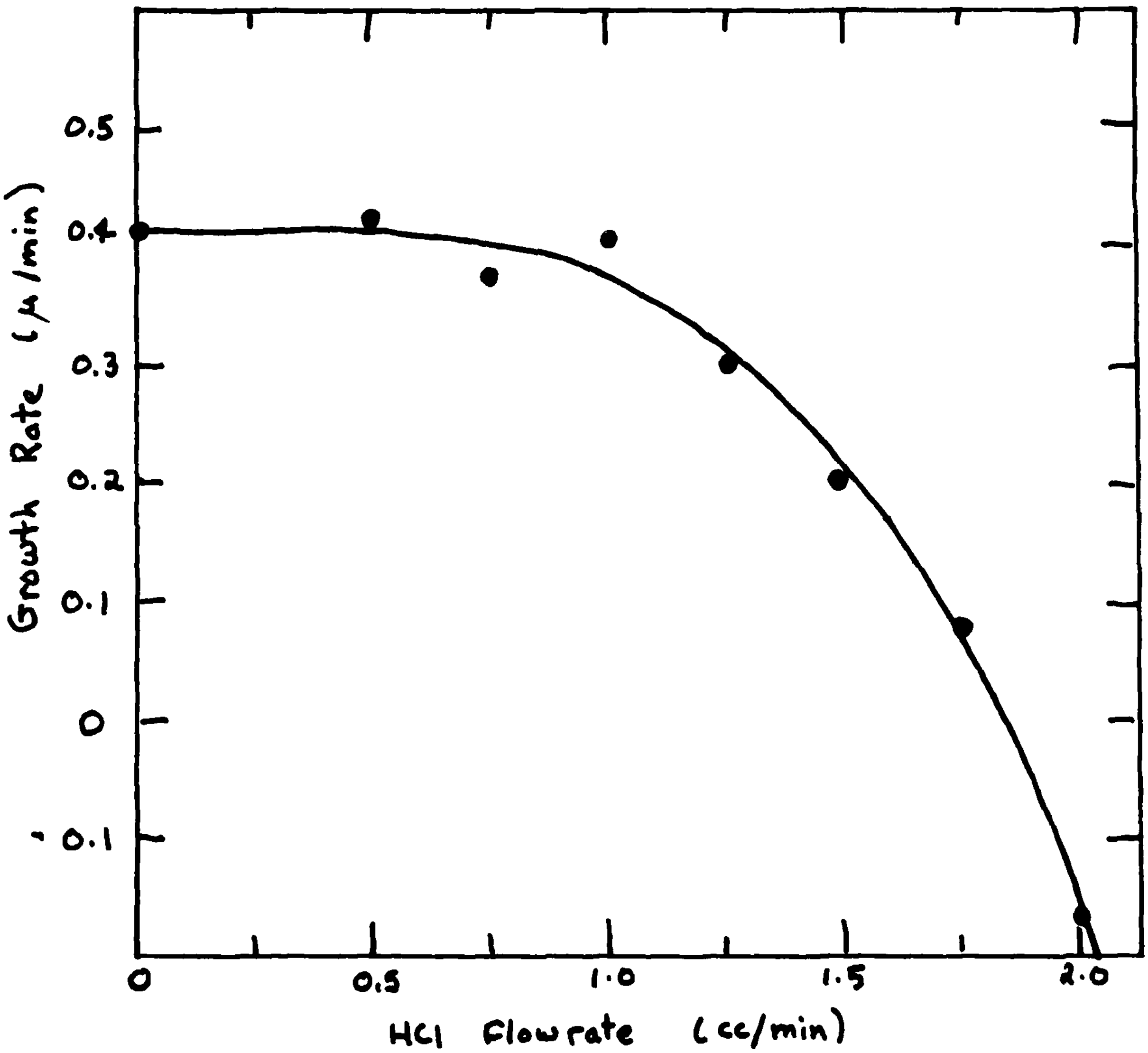

Figure 10. Growth rate versus sidestream HCl flowrate.

proposed that the rate limiting step for Si incorporation is the adsorption Si atoms and thus an increase in P ad-atoms should decrease the free carrier concentration via a blocking mechanism. According to Pogge and Kemlage, an increase in the P_4 partial pressure is most effective in preventing Si incorporation. One method of changing the phosphorous makeup of the reaction gas mixture is to change the mixing zone temperature which should produce a change in the extent of PH_3 decomposition. According to Ban, a rather substantial alteration in the phosphorous makeup ($PH_3:P_4:P_2$) can be enacted by simply changing the decomposition temperature. A change in the center zone temperature should influence the gas phase composition as the PH_3 residence time in this zone is approximately 5 times as that in the source zone as a result of the difference in tube diameters. Additionally, one might expect a small change in the extent of HCl interaction with the quartz wall as the temperature is varied.

Two series of experiments were performed in which the center zone temperature was varied between 675 and 975°C in both an increasing and decreasing manner. The electrical properties of the grown epitaxial films are displayed in Figures 11-14 and indicate conflicting results. As the temperature is reduced with a given series of deposits, the free carrier concentration showed an apparent maximum (Figure 11) while increasing the temperature produced a minimum in the free carrier concentration and occurred at the same temperature as the maximum. As in the previous experiments, the variation of the measured electrical properties was indeed quite small and could possibly be attributed to experimental error. Additionally, the work of Ban[11] indicated that varying the temperature of a flowing PH_3-AsH_3 mixture changes the amount of P_4 very little, predominantly affecting the PH_3/P_2 ratio. If, as suggested by Pogge, the P_4 amount primarily determined the Si impurity level then little effect might be expected here.

VII. RECOMMENDATIONS

In contrast to InP deposition in the chloride system and GaAs in both the hydride and chloride processes, no major effect of certain reaction variables on the electrical properties of the deposited films could be found. The reason for this apparent discrepancy is not obvious.

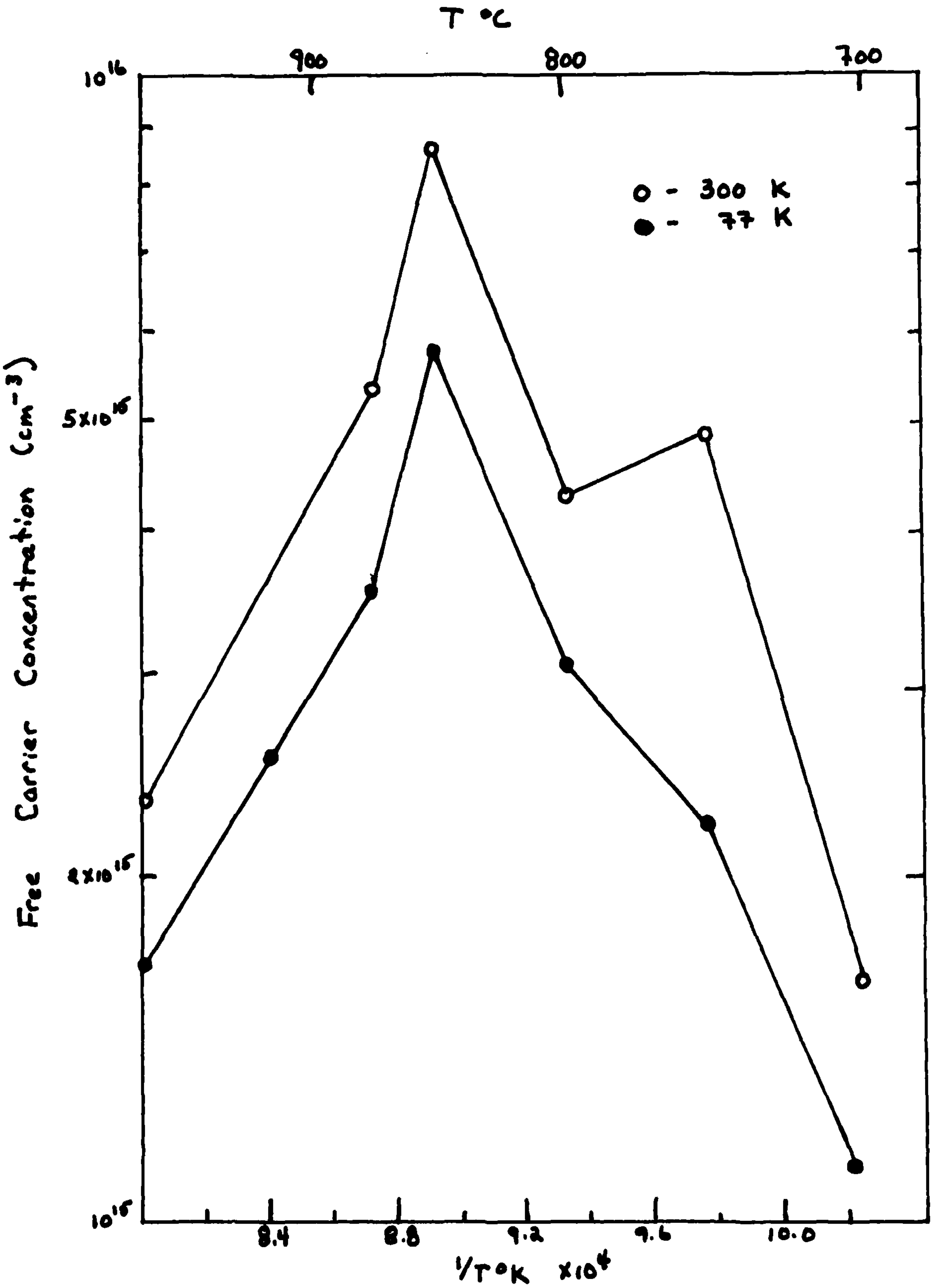

Figure 11. Free carrier concentraion versus center zone temperature.

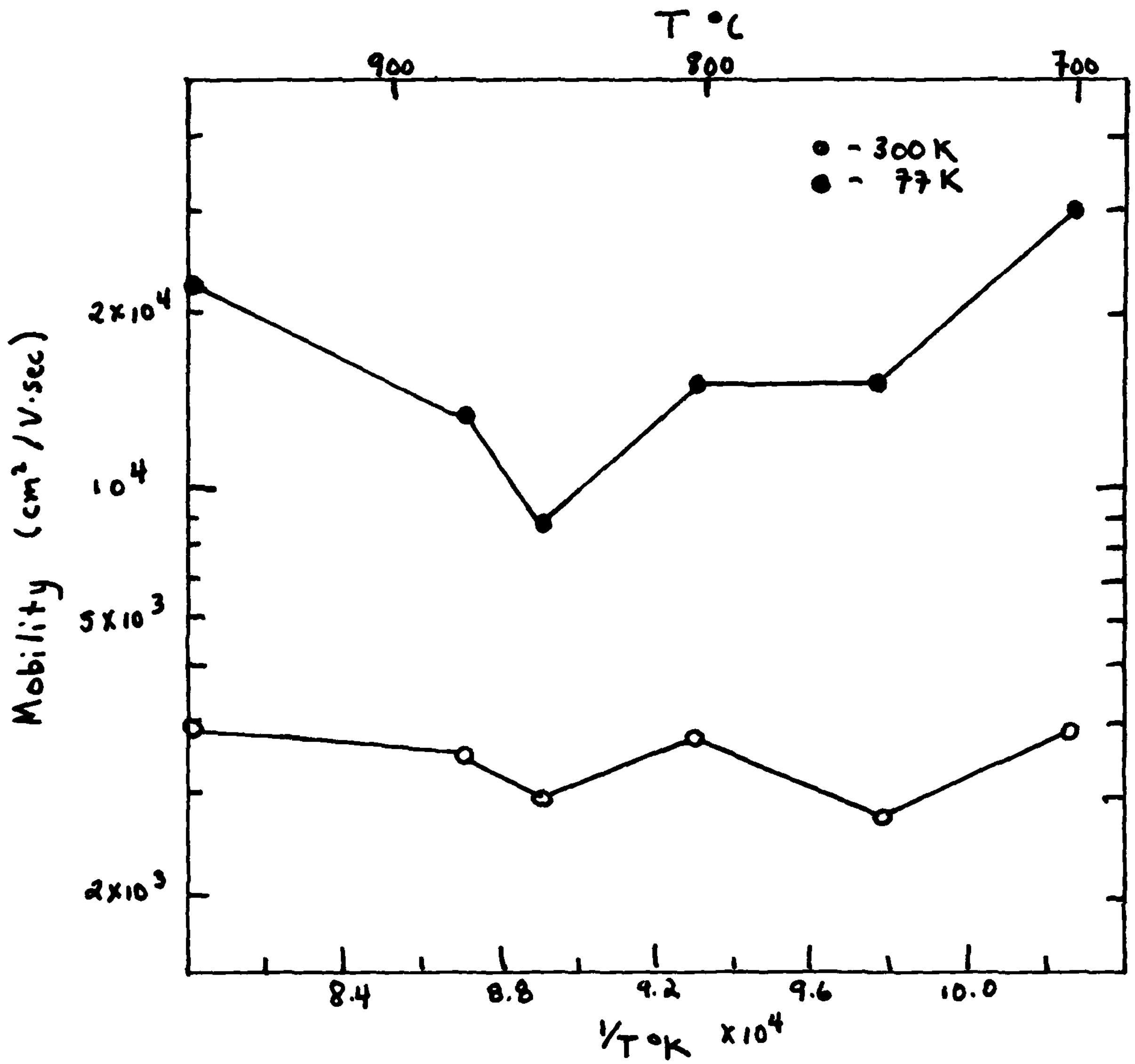

Figure 12. Electron mobility versus center zone temperature.

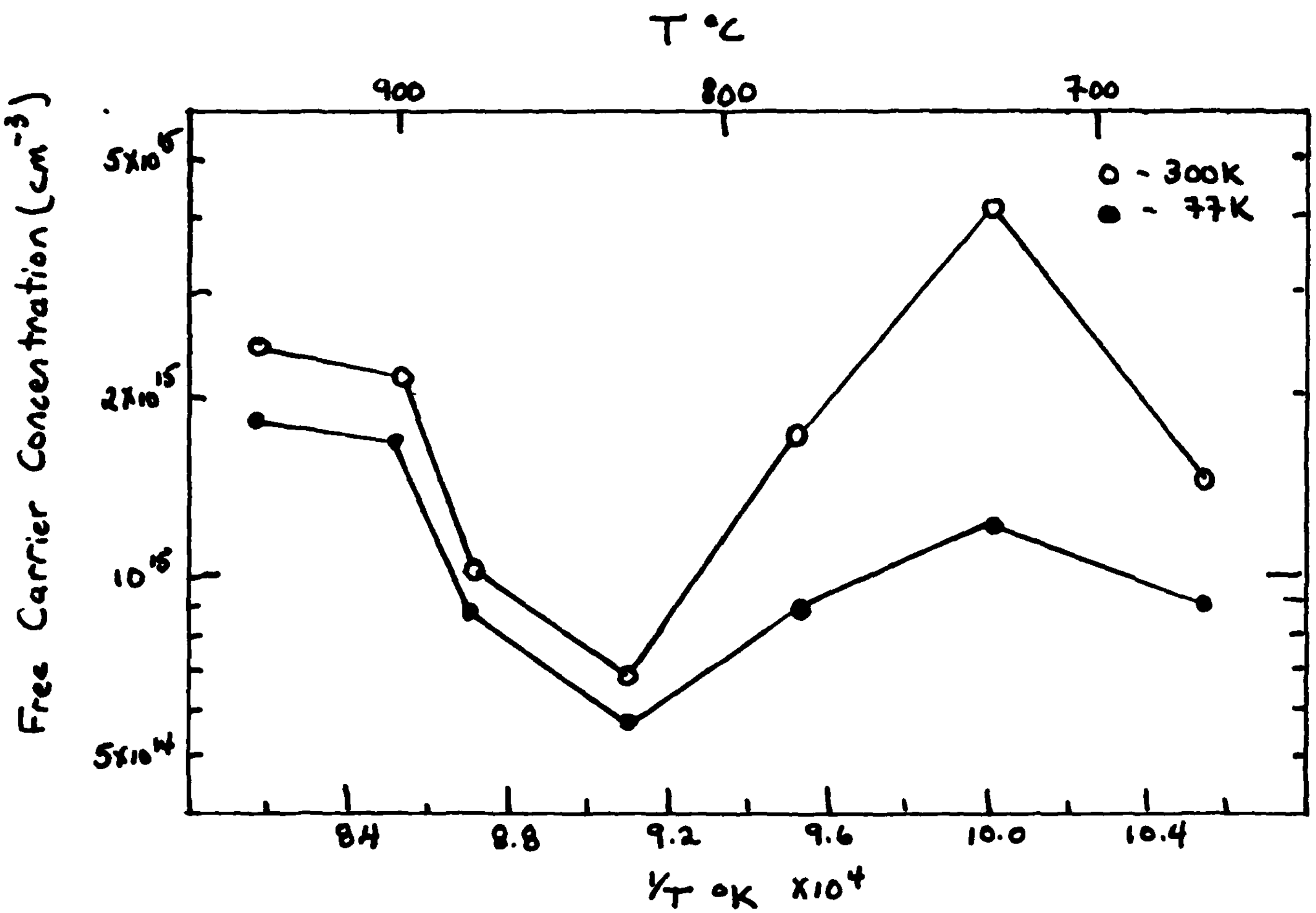

Figure 13. Free carrier concentration versus center zone temperature.

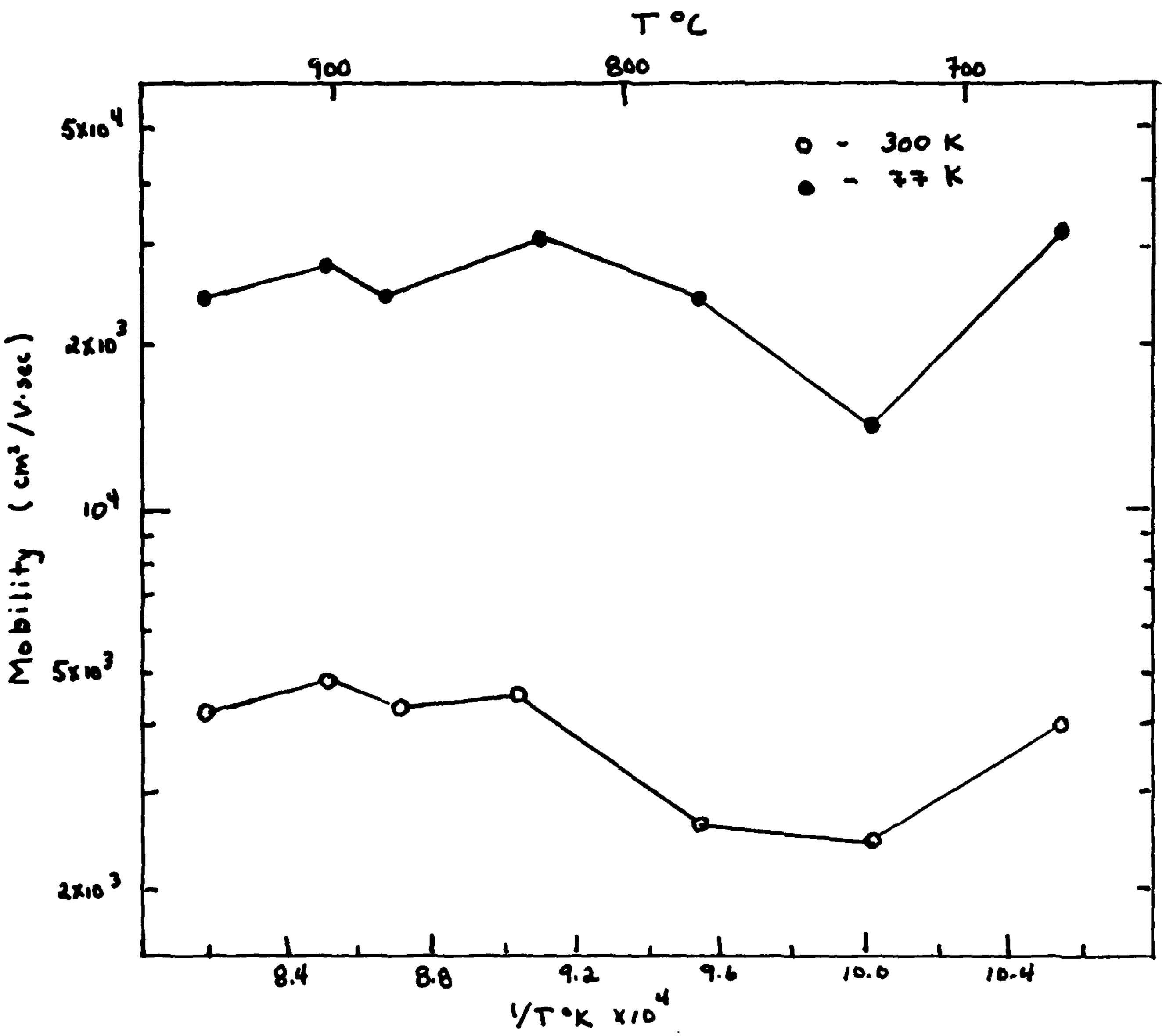

Figure 14. Electron mobility versus center zone temperature.

Not until a better understanding is gained of the chemistry and engineering of these two processes can one hope to design vapor phase epitaxial reactors for production of films with controlled properties. The first step of such an analysis would be to establish the thermodynamic limitations that are so useful in discerning the possible from the impossible. In particular, a combined chemical and phase equilibrium calculation that includes both the gas phase and the defective solid would be important for understanding the impurity incorporation mechanism. As a second step a model that accounts for the mass transport and kinetics of the deposition process would be useful for comparing the hydride and chloride processes since it is these time dependent phenomena that give rise to the differences in the two methods. Such modelling efforts can provide a simple means of analyzing experimental results and are useful in suggesting design alterations. Very little is understood about the amounts and reactivity of the specie present in the vapor phase epitaxial reactor and an experimental program designed to elucidate the quantitative chemistry of the process would be invaluable. Until this basic understanding of the chemical engineering of the process is realized, VPE of III-V semiconductor materials will remain in the realm of art.

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FINAL REPORT

MOLECULAR ABSORPTION IN THE FAR WINGS

Prepared by: Dr. Robert L. Armstrong

Academic Rank: Associate Professor

Department and University: Department of Physics, New Mexico State University

Research Location: Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts

USAF Research Colleague: Dr. Robert A. McClatchey

Date: September 5, 1980

Contract No: F49620-79-C-0038

MOLECULAR ABSORPTION IN THE FAR WINGS

by

Robert L. Armstrong

ABSTRACT

The results of a theoretical investigation of molecular absorption in the far wings of spectral lines is reported. General properties of the spectrum and the related Fourier transform dipole auto-correlation function are examined as providing a guide to the selection of a model spectral profile. A model spectrum for line wing absorption is considered in detail. Model parameters are related to kinematical and dynamical properties of the absorbing molecules using the known spectral moments. The model spectral profile is applied to the analysis of the spectrum of the high-frequency wing of the ν_3 band of CO_2. Agreement between theory and available experimental data is qualitatively good but quantitative discrepancies exist. A number of extensions to the research reported here are suggested to improve the fit between theory and experiment, and to investigate other spectral regions of interest.

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I. INTRODUCTION AND OBJECTIVES

The absorption of electromagnetic radiation by molecules in the earth's atmosphere is an important physical process in the study of a variety of atmospheric transmittance problems. These include analysis of the propagation of laser radiation through the atmosphere in communications and laser radar systems, and the inversion of satellite-based radiometric measurements of upwelling terrestrial radiance to retrieve atmospheric temperature profiles. The theoretical determination of atmospheric transmittance requires a knowledge of the line parameters of all absorbing species present in significant concentrations along the path of the radiation. Line parameter data is conveniently available for a number of atmospheric constituents in the AFGL line parameter compilation.[1] The absorption line shape must also be known in order to compute the atmospheric transmittance. Near the center of an isolated absorption line the theoretical prediction of the line shape based on the impact approximation[2] agrees well with experimental measurements. In this frequency domain a Lorentzian profile adequately describes the line shape at moderate pressures. As the pressure is reduced the Lorentzian line shape must be convolved with a Doppler profile. For extremely narrow pressure broadening half-widths as, for example, in the case of water vapor lines[3] of high rotational quantum number, J, collision narrowing effects must also be taken into account.[4]

When the line density is high as, for example, near Q-branches, line mixing effects[5] may be included within the theoretical framework of the impact approximation. Quantitative comparisons with experimental data in this case are difficult because line mixing theories contain not only isolated line-width parameters, but, in addition, mixing parameters that individually give the fractional amplitude of a given line transferred to another line by collisions. An approximate method has been developed,[6] however, for dealing with this problem. The resulting corrections to the line shape are in fact small at the moderate pressures found in the earth's atmosphere, and are generally ignored in spectroscopic studies.

In the wings, far from the center of either an isolated absorption line or an absorption band the theoretical basis from which to calculate the absorption line shape is much less satisfactory. The impact approximation, in which molecular collisions are assumed to take place instantaneously, is known to fail in the line wings.[7] An adequate theory of wing absorption must take proper account of molecular collisions on a time scale of the order of the duration of a collision. This requirement has resulted in a number of model wing absorption profiles that contain a "duration of collision" parameter.[8,9] Further, line mixing effects may be relatively large in this wing region[8] by virtue of the fact that a large number of lines from both near and distant bands overlap in this frequency domain, whereas the absorption due to any given line is itself extremely small.

In this report, the results of a study of wing absorption line profiles is presented. The theoretical basis for computing the line shape is given in Section II. Section III discusses certain general properties of the model line shape that may be used to place limits on the validity of a particular model line shape function. In Section IV a specific model line shape function is applied to the analysis of available experimental data. Finally, in Section V the conclusions of this study are given together with recommendations for further work.

II. ABSORPTION LINE PROFILE

In this section we obtain an expression for the absorption line shape that may be compared with experimental data on wing absorption. Experimentally, the transmittance τ is measured over some frequency domain of interest. The transmittance at the frequency ω is given by:

$$\tau = I/I_o = e^{-\sigma n \ell}, \tag{1}$$

where I_o and I are the incident intensity and the intensity remaining after a path length ℓ of absorber has been traversed, respectively, n is the number density of absorber molecules (we assume n = constant along the path ℓ throughout this report) and σ is the absorption cross section per molecule. In terms of the Schrödinger picture of quantum

mechanics σ may be expressed in the form:[10]

$$\sigma = \frac{4\pi^2}{\hbar c} \sum_{i,f} \rho_i |< i|\hat{\varepsilon}\cdot\vec{\mu}|f >|^2 \omega_{if}(1-e^{-\hbar\omega_{if}/kT})\delta(\omega_{if}-\omega), \qquad (2)$$

where the subscripts i and f denote the initial and final states of the system of interacting molecules corresponding to the transition $\omega_{if} = (E_f-E_i)/\hbar$, $\rho_i = e^{-E_i/kT}/Q$ is the probability that the molecule is in the i^{th} initial state (with Q the partition function), $\hat{\varepsilon}$ is a unit vector along the direction of the incident electric field and $\vec{\mu}$ is the electric dipole moment operator of the absorbing molecule. For an isotropic sample the same result is obtained when an average is performed over the polarization directions. The cross section then becomes:

$$\sigma = \frac{4\pi^2\ \omega(1-e^{-h\omega/kT})}{3\hbar c}\ \phi(\omega) \qquad (3)$$

with

$$\phi(\omega) = \sum_{i,f} \rho_i |< i|\vec{\mu}|f >|^2 \delta(\omega_{if}-\omega), \qquad (4)$$

and where the frequency terms have been factored out of the sums by making use of the properties of the δ-functions.

Gordon[10] points out that Eq. (4) may be written in terms of the Heisenberg picture of quantum mechanics with the accrued advantage of enhanced "interpretive value", and with the further advantage that theoretical models of the spectrum may be more readily compared with appropriate experimentally derived functionals of the observed spectrum. In the Heisenberg picture Eq. (4) becomes:

$$\phi(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dt\ C(t)e^{-i\omega t}, \qquad (5)$$

where

$$C(t) = < \vec{\mu}(o)\cdot\vec{\mu}(t) >$$

$$= \sum_i \rho_i < i|\vec{\mu}(o)\cdot\vec{\mu}(t)|i > , \tag{6}$$

is the ensemble-averaged auto-correlation function of the Heisenberg dipole moment operator. It is convenient to define a reduced auto-correlation function $C_{if}(t)$ that corresponds to a given observed transition of the absorbing molecule. Provided line mixing effects may be neglected, the trace in Eq. (6), performed in terms of the wave functions for the free molecule, has the form:[11]

$$C(t) = \sum_{i,f} \sum_{d_i d_f} \rho_i <i,d_i|\vec{\mu}(o)|f,d_f><f,d_f|\vec{\mu}(t)|i,d_i> , \tag{7}$$

where the subscripts i and f now label the degenerate energy levels of the initial and final states, respectively, and d_i and d_f are the degeneracies of these two states. For example, for a vibration-rotation band i and f denote the vibrational and rotational quantum numbers v and J of the initial and final states, respectively, and d_i and d_f denote the degeneracy associated with the magnetic quantum number M (and K or ℓ for a symmetric top molecule or for a perpendicular band of a linear molecule). Then the reduced auto-correlation function $C_{if}(t)$ may be defined by:

$$C(t) = \sum_{i,f} \rho_i |\mu_{if}|^2 e^{i\omega_{if}t} C_{if}(t), \tag{8}$$

where

$$|\mu_{if}|^2 = \sum_{d_i,d_f} | < i,d_i|\mu(o)|f,d_f>|^2. \tag{9}$$

For example, for a vibration-rotation band $|\mu_{if}|^2 = |\mu_{vv'}|^2 M_{J,J'}$, where $|\mu_{vv'}|^2$ is the vibrational matrix element and $M_{JJ'}$ is the Hönl-London factor.[12] The spectrum given by Eq. (5) is then of the form:

$$\phi(\omega) = \sum_{i,f} \rho_i |\mu_{if}|^2 \, \Gamma_{if}(\omega), \tag{10}$$

where the reduced spectrum:

$$\Gamma_{if}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dt \; C_{if}(t) e^{i(\omega_{if}-\omega)t}. \tag{11}$$

Equation (10) is seen to be of the form of a sum of terms, each of which gives the absorption of an individual line with a strength proportional to $\rho_i |\mu_{if}|^2$ and a reduced spectrum $\Gamma_{if}(\omega)$.

III. GENERAL PROPERTIES

In this section general properties of the spectrum $\phi(\omega)$ or the corresponding auto-correlation function $C(t)$ are discussed. These properties are useful in that they both guide experimental studies to optimize comparison with theoretical spectral models and conversely provide checks on the validity of the theoretical models themselves when compared with the results of experiment. The properties discussed here are not intended to constitute a complete list and complement discussions given elsewhere.[9]

The spectrum $\phi(\omega)$ is a real measured quantity. The analogous reality condition on the auto-correlation function $C(t)$ is:[5]

$$C(t) = C^*(-t), \tag{12}$$

which implies that $\mathrm{Re}C(t)$ and $\mathrm{Im}C(t)$ are even and odd functions of the time, respectively. It may be further shown[5] that in the classical limit ($\hbar\omega \ll kT$) $C(t)$ becomes a real (and hence even) function of the time. Thus, a non-vanishing imaginary part of $C(t)$, as seen below, constitutes a quantum correction.

An additional constraint on the spectrum is imposed by the principle of detailed balance.[13] This constraint arises because the relative populations of each pair of levels contributing to the

absorption spectrum $\phi(\omega)$ and the emission spectrum $\phi(-\omega)$ are related by a Boltzmann factor under conditions of thermodynamic equilibrium. The constraint on the spectrum is:

$$\phi(-\omega) = e^{-\hbar\omega/kT}\ \phi(\omega), \tag{13}$$

and the corresponding constraint on the auto-correlation function has the form:[11]

$$C(-t) = C(t + ih/kT). \tag{14}$$

The principle of detailed balance also results in a relation between the real and imaginary parts of C(t):[5]

$$\mathrm{Im}C(t) = -\tanh \hbar/2kT \frac{\partial}{\partial t} \mathrm{Re}C(t). \tag{15}$$

Thus, if the real part of C(t) is known the imaginary part may be found from Eq. (5).

An additional set of constraints on the auto-correlation function is related to the expansion of C(t) in a Taylor series in the time:

$$C(t) = \sum_{n=0}^{\infty} C^{(n)}(0)\ \frac{t^n}{n!}, \tag{16}$$

where $C^{(n)}(0)$ is the n^{th} time derivative of C(t) evaluated at t = 0. It may also be shown[5] that the Taylor series expansion of C(t) is related to the moments of the spectrum $\phi(\omega)$ according to:

$$C(t) = \sum_{n=0}^{\infty} M_n \frac{(it)^n}{n!}, \tag{17}$$

where the n^{th} spectral moment:

$$M_n = \int \omega^n\ \phi(\omega)d\omega. \tag{18}$$

Therefore, in the Taylor-series expansion of C(t):

$$C^{(n)}(0) = (i)^n M_n, \tag{19}$$

and in principle C(t) can be computed or measured directly from a knowledge of the spectral moments.

The moments of an infrared molecular spectrum have been computed in general terms by Gordon.[14] For example, for the simplest case of a diatomic molecule or for a parallel transition in a linear molecule, Gordon finds (to fourth order):

$$M_1 = \hbar/I, \tag{20a}$$

$$M_2 = \frac{2kT}{I}, \tag{20b}$$

$$M_3 = \frac{4\hbar kT}{I^2} + \frac{\hbar\langle k^2\rangle}{2kTI^2}, \tag{20c}$$

$$M_4 = \frac{8k^2T^2}{I^2} + \frac{\langle k^2\rangle}{I^2}, \tag{20d}$$

where I is the moment of inertia, $\langle k^2\rangle$ is the mean square torque acting on the absorbing molecule due to collisions and where small correction terms $\sim\hbar^2$ or higher have been omitted. Equations (20a) - (20d) may then be used either to validate an exact spectral theory or to serve as a guide to the physical interpretation of a parametric theory. For example, Eqs. (20a) - (20d) show that the first two moments contain only a kinematical part proportional to T, whereas the third and higher moments contain both a kinematical and a dynamical part proportional to the mean squared torque acting on the absorbing molecule. The correlation function for an exact theory for such a system should then exhibit the same properties. Further, the interpretation of the physical significance of parameters in a model theory may be guided by comparison with the known moments.

It should be noted that the time expansion of the auto-correlation function in Eq. (16) converges rapidly only for short times and that an increasing number of spectral moments are required to carry the

expansion out to longer times. In practice[5] the expansion of C(t) need only converge out to a time of the order of the duration of an average collision, after which the impact approximation becomes valid.

Since in any practical case only a small number of moments are known, it becomes a matter of importance to inquire whether any limits can be placed on the form of the spectrum that has the known moments. Gordon[15] has investigated this problem and developed expressions for error bounds that may be placed on the spectral density by virtue of the fact that it has a finite number of known moments. As an example, consider the cumulative spectral distribution:

$$D(\omega_0) = \int_{-\infty}^{\omega_0} I(\omega)d\omega \ . \tag{21}$$

Since

$$0 \leq D(\omega_0) \lesssim M_o, \tag{22}$$

where M_o is the 0^{th} moment of the spectrum, Gordon inquires whether more precise bounds can be placed on $I(\omega)$ if higher moments are known. He finds that two extremal cumulative spectral distributions may be constructed, each having the known spectral moments, such that:

$$D_{min}(\omega_0) \leq D(\omega_0) \lesssim D_{max}(\omega), \tag{23}$$

and further, that no more precise error bounds may be placed on $D(\omega_0)$ corresponding to the given moment information. Gordon derives expressions for extremal distributions associated with several other functionals of the observed spectrum. In each case the extremal distributions possess the same known moments as the observed spectrum and furnish additional error bounds on the spectrum.

IV. WING ABSORPTION MODEL

In this section we consider a specific line profile that may be used to investigate absorption in the wings of spectral lines or absorption bands. This model is then applied to the analysis of available data on the high frequency wing of the ν_3 band of CO_2.

Birnbaum[8] has considered a model of the absorption line shape which is suitable for wing absorption studies. Line mixing effects are neglected in this model so the absorption spectrum is a sum of individual line absorption terms. The reduced spectrum, $\Gamma_{if}(\omega)$, is computed in Birnbaum's model from the reduced auto-correlation function:

$$C_{if}(t) = \exp\{\tau_1^{-1}(\tau_2-(\tau_2^2+y^2)^{\frac{1}{2}})\}, \qquad (24)$$

where τ_1 and τ_2 are time parameters of the model, and y is the complex time:[16]

$$y = (t^2 - i\hbar t/kT)^{\frac{1}{2}}. \qquad (25)$$

With this form of the model reduced auto-correlation function the reality condition, Eq. (12) is satisfied. Moreover, the principal of detailed balance, given by Eq. (14), and the collateral relationship between ReC(t) and ImC(t), Eq. (15), are found to hold. At long times $t >> \hbar/kT$:

$$C_{if} \cong e^{\frac{1}{\tau_1}(\tau_2 \pm i\tau_o - |t|)}, \qquad (26)$$

where $\tau_o = \hbar/2kT$. From Eq. (26) τ_1^{-1} may be identified with the pressure-broadened half width $\alpha = \tau_1^{-1}$. In this model τ_o is seen to play the role of a "thermal time" which insures that the absorption profile satisfies detailed balance. The parameter τ_2 is an effective duration of collision parameter and is related to the mean square torque acting on the molecule during a collision.

To investigate the physical significance of τ_2 we consider the short-time expansion of the auto-correlation function C(t) given by

Eq. (8). Since Eq. (15) relating the real and imaginary parts of C(t) is satisfied, it is sufficient to expand ReC(t). For the particular case of a parallel transition in a linear molecule we get[8] (for a given vibrational transition):

$$\mathrm{Re}C(t) = 1 - \frac{t^2}{2!}\left[\frac{2kT}{I} + \frac{1}{\tau_1\tau_2}\right] + \frac{t^4}{4!}\left[\frac{8k^2T^2}{I^2} + \frac{3(\tau_1+\tau_2)}{\tau_1^2\tau_2^3} + \frac{12\ kT}{\tau_1\tau_2 I}\right] + \ldots \quad (27)$$

In terms of the spectral moments, Eq. (17):

$$\mathrm{Re}C(t) = 1 - \frac{t^2}{2} M_2 + \frac{t^4}{4!} M_4 + \ldots , \quad (28)$$

with the result (to fourth order):

$$M_2 = \frac{2kT}{I} + \frac{1}{\tau_1\tau_2} , \quad (29a)$$

$$M_4 = \frac{8k^2T^2}{I^2} + \frac{3(\tau_1+\tau_2)}{\tau_1^2\tau_2^3} + \frac{12kT}{\tau_1\tau_2 I} . \quad (29b)$$

A comparison of the above expressions for M_2 and M_4 with the exact expressions obtained by Gordon, Eqs. (20b) and (20d), reveals that the second moment should contain only a kinematical term and the fourth moment both a kinematical and a dynamical term. A qualitative argument may be made relating the second term in the fourth moment of the model correlation function, Eq. (29b) to this dynamical term. Consider a classical molecular dipole viewed from a coordinate system rotating with the freely rotating molecule (this choice of coordinate system effectively removes the kinematical term from the spectral moment). As a result of a collision a dipole originally oriented along an axis of this coordinate system will be de-phased by an angle θ.

The relaxation model of this process gives for such a collision:

$$\mu^{(1)}(t) = -\mu(t)/\tau_2, \tag{30}$$

where τ_2 now denotes a relaxation time characteristic of the duration of the collision. For a collision beginning at t=0 Eq. (30) has the solution $\mu(t) = \mu(o)e^{-t/\tau_2}$, from which we find $|\mu^{(4)}(o)/\mu(o)| = |\mu^{(2)}(o)/\mu(o)|^2 = 1/\tau_2^4 = |\theta^{(2)}(o)|^2$. Since $\theta^{(2)} = k/I$ we have:

$$|\mu^{(4)}(o)/\mu(o)| = 1/\tau_2^4 = k^2/I^2. \tag{31}$$

We have so far considered the effect of a single collision. When we average over an ensemble of dipoles, or, equivalently, average a single dipole over a long time in which many collisions occur, we must take into account the fact that the molecule undergoes a collision only a fraction τ_2/τ_1 of the time, where τ_1 is the time between collisions, and where we assume $\tau_1 >> \tau_2$. Then we get (for the dynamical term in M_4 only):

$$M_4 = C^{(4)}(o) = <|\mu^{(4)}(o)/\mu(o)|> = (\tau_2/\tau_1)(1/\tau_2^4) = (1/\tau_1\tau_2^3) = <K^2>/I^2. \tag{32}$$

When the second terms in Eq. (29b) and Eq. (20d) are compared we get:

$$\frac{3(\tau_1+\tau_2)}{\tau_1^2\tau_2^3} \cong \frac{3}{\tau_1\tau_2^3} \simeq \frac{1}{\tau_1\tau_2^3} = \frac{<K^2>}{I^2}, \tag{33}$$

by Eq. (32). Thus we see that the model parameter τ_2 may be related to the mean square torque acting on the molecule.

There remains the discrepancy associated with the extra terms found in the second and fourth moments of the model correlation function but not present in the exact expressions derived by Gordon. For example, in the second moment the term $(1/\tau_1\tau_2)$ is not present in Gordon's exact expression, while in the fourth moment $(12KT/\tau_1\tau_2 I)$ is an extra term. Birnbaum has attempted to eliminate these terms by the addition of a correction term to the reduced auto-correlation

function, Eq. (24). The initial attempt contained an error although it now appears possible[17] to eliminate the undesirable term in the fourth moment but not in the second. In any event the undesirable term in the second moment is small ($\sim 10^{-2}$) compared to the first kinematical term. In the fourth moment the undesirable term is also $\sim 10^{-2}$ the kinematical term but is of the same order as the dynamical term that is related to the mean square torque. Thus, it would be desirable to include the correction term in the correlation function and study the effect of this correction term on the spectral profile. Such a study was not done in the work reported here but is proposed in Section V as additional needed research.

Returning to the model correlation function developed by Birnbaum,[8] but without the correction term,[17] the spectrum $\phi(\omega)$ in Eq. (4) may be written:

$$\phi(\omega) = \sum_{i<f} |\mu_{if}|^2 [\rho_i \Gamma_{if}(\omega_-) + \rho_f \Gamma_{if}(\omega_+)], \tag{34}$$

with

$$\Gamma_{if}(\omega_\pm) = e^{\tau_2/\tau_1} e^{\tau_o \omega_\pm} L(\omega_\pm) Z_\pm K_1(Z_\pm),$$

$$\omega_\pm = \omega \pm \omega_{if},$$

$$Z_\pm = [(\tau_o^2 + \tau_2^2)(1+\tau_1^2\omega_\pm^2)]^{\frac{1}{2}},$$

where $L(\omega_\pm)$ is a normalized Lorentzian profile and K_1 is the modified Bessel function of the second kind. The emission term $\Gamma_{if}(\omega_+)$ is extremely small compared to the absorption term $\Gamma_{if}(\omega_-)$ in the infrared and in fact is omitted from the detailed calculations that follow. Note that near line center $Z_- \ll 1$, $Z_- K_1(Z_-) \sim 1$ and the spectrum essentially reduces to a sum of Lorentzians. In the line wings $Z_- \gg 1$ $K_1(Z_-) = (\pi/2Z_-)^{\frac{1}{2}} e^{-|Z_-|}$ and the spectrum exhibits the well-known exponential frequency dependence.

To facilitate the detailed comparison with experimental data, it is convenient to cast the spectrum in a form suitable for numerical

calculations. The transmittance given by Eq. (1) may be written as:[18]

$$\tau = e^{-ku}, \tag{35}$$

where $u = \ell \frac{P/P_o}{T/T_o}$ is the absorber thickness scaled to standard temperature and pressure (T_o = 273K and P_o = 1 atm), and the absorption coefficient:

$$k = \frac{4\pi^2 \; n_o \omega(1-e^{-\hbar\omega/kT})}{3\hbar c} \sum_{i<f} \rho_i |\mu_{if}|^2 \; \Gamma_{if}(\omega\_), \tag{36}$$

where n_o = 2.69 x 10^{19} mols/cm = 1 $(\text{cm-atm})_{STP}$. For a given vibration-rotation band, the absorption coefficient can be expressed in terms of appropriately defined line strengths as:

$$k = \sum_J S_{v,J}(T)\Gamma_{v,J}(\omega\_), \tag{37}$$

with the line strength:[19]

$$S_{v,J}(T) = S_v^o \; \rho_J \; H_J \; \frac{\omega_{v,J}(1-e^{-hc\omega_{v,J}/kT})}{\omega_{v,o}(1-e^{-hc\omega_{v,o}/kT})} , \tag{38}$$

where S_v^o is the integrated band intensity, ρ_J is the fractional population in the state J, M_J is the Hönl-London factor for the given vibration-rotation line and where frequencies are now expressed in cm^{-1}. The line strengths, lower state energies and line half-widths are available for a number of molecules of atmospheric interest in the AFGL line parameters listing[1] at a reference temperature and pressure of 296K and 1 atm, respectively. The line strength may be scaled according to:

$$S_{v,J}(T) = S_{v,J}(296) \frac{A(T)}{A(T_o)} , \tag{39}$$

where

$$A(T) = \rho_{v,J}(T)(1-e^{-hc\omega_{v,J}/kT}).$$

The line half-width scales according to:

$$\alpha(T) = \alpha(T_o)(296/T)^{\frac{1}{2}}, \tag{40}$$

for the case of a temperature independent collision cross section, and is the temperature scaling used in the following calculations.

Absorption in the far wings of absorption lines is difficult to interpret because of the presence of strong nearby lines or bands. Some notable exceptions occur in the case of the absorption by the HCℓ fundamental[20] and absorption in the high frequency wing of the ν_3 band of CO_2 near 4.3 μm.[7,18] In this report we apply the model spectrum developed by Birnbaum to the study of the latter CO_2 wing absorption. The ν_3 band of CO_2 is a strong band in which the R branch converges to a band head at 2397 cm^{-1}. At higher frequencies within several hundred cm^{-1} of the band head there are no strong bands. Line parameter data is available for this band from the AFGL compilation. Experimental absorption data for this band in the frequency region beyond 2397 cm^{-1} has been taken by Burch et al.[18] and by Winters et al.[7] The experimental absorption coefficients determined by these two groups are plotted in Figure 1 together with a theoretical absorption coefficient obtained by numerically evaluating Eq. (37). Also in Figure 1 we have plotted the theoretical absorption curve assuming a Lorentzian line profile.

It is clear from Figure 1 that the Lorentzian profile is inadequate to describe the experimentally observed absorption coefficients. Further inspection of Figure 1 reveals that a value $\Delta_2(=(2\pi c\tau_2)^{-1}) \simeq$ 27 cm^{-1} provides the best fit to the experimental data. A theoretical estimate for Δ_2 may be obtained by numerically computing the mean square torque for a suitable choice of the inter-molecular potential function. For pure CO_2 Birnbaum chooses a quadrupole-quadrupole interaction and obtains a theoretical estimate of Δ_2 = 14 cm^{-1}, which is approximately a factor of 2 smaller than the "best fit" value of

$\Delta_2 \cong 27$. The fit for $\Delta_2 \cong 27$ is seen to be qualitatively satisfactory but clearly deviations exist and there is a general discrepancy in slope between theory and experiment. Two additional investigations are immediately apparent and would be well worth performing. First, the location of other CO_2 bands is shown on Figure 1. These bands are weak but in the wing of the ν_3 band may produce a significant contribution to the absorption. These bands should be included in the calculation of the absorption coefficient. Second, the correction term to the correlation function suggested by Birnbaum[17] should be incorporated into the calculation of the absorption coefficient.

V. CONCLUSIONS AND RECOMMENDATIONS

In this report we have described the results of a theoretical study of the absorption of electromagnetic radiation by molecules in the far wings of the absorption lines. The impact approximation in which collisions are assumed to occur instantaneously breaks down in the line wings and details of the collisions on a time scale of the order of the duration of a typical collision must be included. We have discussed in detail a specific model of the absorption profile due to Birnbaum. This model was seen to satisfy certain general conditions such as reality and the principle of detailed balance but led to the introduction of spurious terms in the spectral moments not found in the exact moment expressions. Numerical calculations using this model spectrum compared qualitatively with experimental studies of the absorption of CO_2 molecules in the case of the high-frequency wing of the ν_3 fundamental but exhibited quantitative deviations in excess of the scatter in the available experimental data.

Several avenues of continuing research suggest themselves to attempt to improve the fit between theory and experiment. First, other absorption bands of CO_2 should be included in the calculation of the absorption coefficients. These bands are weak but may have a significant effect in the wing region. Second, corrections to the spectral profile suggested by Birnbaum[17] should be included in the calculation. These correction terms result in deleting a term in the

fourth moment of the spectrum that is comparable to the dynamical term used to define the duration of collision parameter τ_2, and might therefore have a measurable effect on the calculated spectrum. Third, the effect of line mixing should be investigated. Rosenkranz,[21] using a technique developed by Gordon,[6] has succeeded in reducing the large number of line parameters present in line mixing theories and has applied the results of this analysis to the study of the O_2 spectrum near 5 mm. The application of Rosenkranz' analysis to infrared absorption bands should be investigated. Finally, the analysis of Gordon, in which error bounds are placed on appropriately defined functionals of the observed spectrum, should be considered as a convenient way to test model spectral profiles for conformity with the known spectral moments.

The results of the analysis described here have been applied initially to the ν_3 band of CO_2 near 4.3 μm. Other spectral regions of current interest should also be studied, notably the 15 μm bands of CO_2 and the water vapor continuum region near 4 μm.

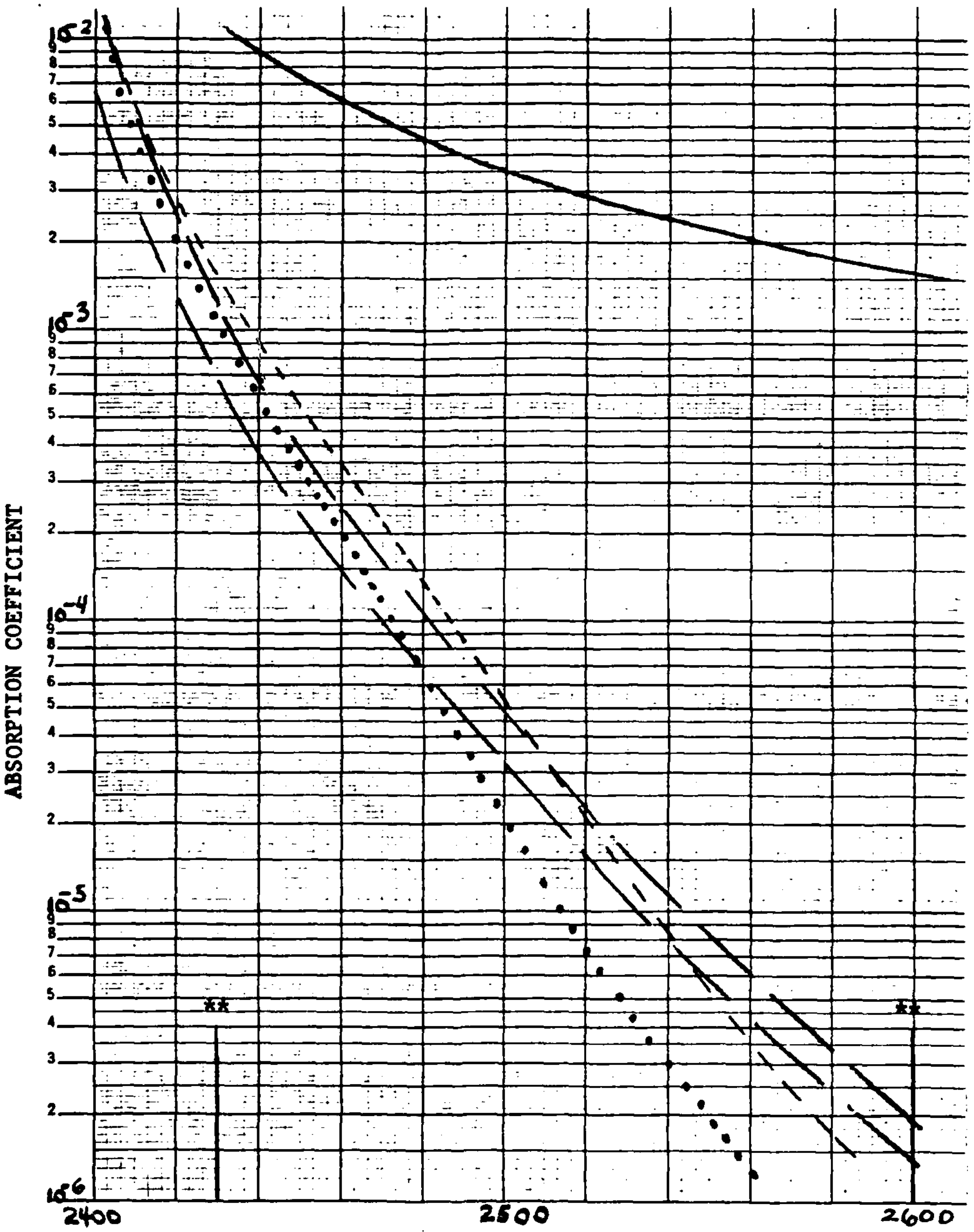

FIGURE 1 - Absorption Coefficient vs Frequency (cm^{-1}), High frequency wing, ν_3 Band of CO_2; ——— ——— —, Brackets Experimental Data of Refs. 7,18; ————, Lorentzian Profile; - - - - - -, Birnbaum's Theory, Δ_2 = 27 cm^{-1}; .... , Birnbaum's Theory, Δ_2 = 23 cm^{-1}; **, location of other CO_2 bands.

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FINAL REPORT

TERATOLOGIC EVALUATION OF A MODEL PERFLUORINATED ACID, NDFDA

Prepared by:	Dr. Inez R. Bacon
Academic Rank:	Professor
Department and University:	Department of Biology University of the District of Columbia
Research Location:	Toxic Hazards Division, Aerospace Medical Research Laboratory
USAF Research Colleague:	Captain William C. Keller
Date:	September 6, 1980
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TERATOLOGIC EVALUATION OF A MODEL PERFLUORINATED ACID, NDFDA

by

Inez R. Bacon

ABSTRACT

The teratogenic effect of a perfluorinated acid, nonadecafluorodecanoic acid(NDFDA), was evaluated in Fisher 344 rats. Rats were given 0, 5, 10, or 15 mg/kg NDFDA by gavage on Day 9 of gestation. Rats were also treated with 0, 10, 20, or 30 mg/kg NDFDA by gavage on Day 12 of gestation. There were no significant differences between treatments and controls at 5, 10, or 15 mg/kg/Day 9 of gestation and 10 or 20 mg/kg/Day 12 of gestation. There was a statistically significant decrease in maternal body weight gain, corpora lutea, resorptions, and mean fetal body weight at 30 mg/kg/Day 12 of gestation. There were no significant differences between experimentals and controls of soft tissue or skeletal abnormalities at any dosage level.

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I. INTRODUCTION

Nonadecafluorodecanoic acid (NDFDA) is a perfluorinated analog of surfactant agents used in fire retardant foams by the Air Force.

The available literature on the toxicity of NDFDA is limited to an "In House" study at the Aerospace Medical Research Laboratory, Toxic Hazards Division, Wright-Patterson AFB, OH. NDFDA was cited as causing histopathological damage to the thymus, bone marrow, stomach, mesentery, liver, and testes in male rats (Andersen, 1979). These results show the effect exposure to NDFDA may exhibit in Air Force men, but do not depict the potential hazard in Air Force women. In view of the need for an evaluation of the teratogenic and/or embryotoxic potential of NDFDA, the present study was conducted.

In this study, groups of pregnant rats were exposed to various dose levels of NDFDA by gavage, and various parameters were evaluated in order to assess the potential teratogenicity during gestation.

II. OBJECTIVES

The primary objective of this study was to determine the teratogenic and/or embryotoxic potential of NDFDA in pregnant rats. The specific objectives were:

(1) To determine an estimated fetal LD_{50}.

(2) To determine gross external abnormalities.

(3) To determine soft tissue and skeletal abnormalities.

(4) To determine the number of implantations and resorptions per litter.

III. METHODS

Materials and Animals. NDFDA, purity 98%, was used in this study. Fisher 344 rats were housed in plastic cages in a room with controlled temperature (70-76F) and light cycle (12 h light and dark). The animals were maintained on Ralston Purina Labratory Chow and tap water *ad libitum.* The rats were allowed to acclimatize one week to their environment before use. The day on which sperm was observed in a vaginal smear was considered Day 0 of gestation.

Procedure. NDFDA was given in propylene glycol and water(50:50) at a dose volume of 2 ml/kg body weight. Pregnant rats were given 5, 10, or 15 mg/kg NDFDA once on Day 9 of gestation and 10, 20, or 30 mg/kg NDFDA on Day 12 of gestation. Control rats were given the vehicle. These dose levels were selected on the basis of a preliminary study in which severe weight loss and maternal death occurred in females dosed with 20 mg/kg NDFDA on Day 9 of gestation. Females dosed with the same concentration on Day 12 of gestation remained viable.

Observations and fetal examination. The animals were observed daily from Day 9 or 12 of gestation until sacrifice for indications of toxicity from NDFDA. Maternal body weights were recorded daily. Dams were sacrificed by halothane inhalation on Day 20 of gestation.

Using the method of Olson and Back (1978), the number of corpora lutea, implantations, live and / or dead and resorbed fetuses were noted. The position of fetuses in the uterus, sex of fetuses, external examination, and weights were also recorded. After being weighed, one-half($\frac{1}{2}$) of the fetuses from each litter were fixed in absolute ethyl alcohol for subsequent clearing and staining with alizarin red S (Dawson,1926) to permit examination for skeletal abnormalities.The remaining fetuses were fixed in Bouin's solution and sectioned according to the method of Wilson and Warkany(1965) in order to detect internal malformations of the soft tissue.

Statistical analysis of results. The incidence of implantations per female, fetal resorptions, viable fetuses, body weights, skeletal and soft tissue abnormalities were evaluated by the T-test. In all cases, the level of significance chosen was $p<0.05$.

IV. RESULTS

Administration of 30 mg/kg/Day 12 of gestation produced significant maternal toxicity in rats (decreased body weight gain)(Table 2). At 20 mg/kg/Day 9 gestation, 6 of 6 females died. In comparison, no maternal deaths were observed among rats administered 10,20, or 30 mg/kg/Day 12 of gestation. There was a significant difference in corpora lutea, resorptions, and live fetuses per litter for dams treated with 30 mg/kg

NDFDA/Day 12 of gestation(Table 2). However, there was no significant difference between control and experimental implantation sites. The mean fetal body weight from 30 mg/kg/Day 12 dams was significantly lower than the control values ($p<0.002$). Day 9 controls and tests were not significantly different(Table 1).

Malformations observed among the litters of rats given NDFDA did not occur at an incidence significantly different from that of the control rats (Table 3). The only malformation observed in the experimental litters which was not observed among either of the control groups was one case of microphthalmia at 5 mg/kg/Day 9 of gestation.

V. DISCUSSION

Evidence of teratogenicity was not observed in fetuses of dams administered NDFDA by gavage on Day 9 of gestation. Toxic effects in fetuses occurred only in the presence of dose-related maternal toxicity (less maternal body weight gain at 30 mg/kg/Day 12 of gestation). There was a significant decrease in the mean fetal body weight among the litters of rats treated with 30 mg/kg/Day 12 of gestation. There was also an increase in resorptions and a corresponding decrease in the number of live fetuses per litter. There was no significant difference between control and experimental soft tissue or skeletal abnormalities at any dosage level. Butcher et al.(1972) reported that some compounds, when administered at the critical stage of organogenesis in doses which do not cause malformations, can induce postnatal toxic effects and lasting behavioral changes in the offsprings. This hypothesis was also supported by Tanimura(1976) and Frohberg(1975 and 1977).

In contrast to maternal death of dams treated with 20 mg/kg NDFDA on Day 9 of gestation, maternal death did not occur among dams treated with 10, 20, or 30 mg/kg NDFDA on Day 12 of gestation. The reason for this phenomenon is not clear,however, differences in the effects may be due to differences in the amount of maternal plasma proteins and/ or other changes as a result of hormonal or enzymatic activity at that stage of pregnancy.

VI. RECOMMENDATIONS

Since fetal toxicity paralled maternal toxicity, it might be useful to conduct postnatal studies to determine whether NDFDA causes behavioral changes in rattlings. As mentioned in the report herein,some compounds which do not cause malformations during the critical stage of organogenesis, exert their effects postnatally. The central nervous system is usually

affected, therefore, a battery of postnatal developmental neurobehavioral studies should determine any postnatal toxicity to NDFDA. Such a study could be accomplished by using the data herein reported and subjecting litters from exposed dams plus control subjects to behavioral tests from two days of age until sacrifice at 21 days of age. The following tests will be conducted: (a) surface righting, (b) mid-air righting,(c) cliff avoidance, (d) swimming development, (e) pivoting and (f) startle.

TABLE 1

REPRODUCTIVE FINDINGS IN RATS TREATED WITH NDFDA ON DAY 9 OF GESTATION

		NDFDA (Mg/Kg) DAYS 9 - 20		
	Vehicle control	5	10	15
Maternal weight gain(g)	54.0 ± 9.3	52.7 ± 12	57.1 ± 15.4	56.1 ± 16.6
Number of litters	23	15	19	19
Corpora lutea / dam[a]	10.7 ± 1.2	11.1 ± 1.8	11.4 ± 1.5	11.2 ± 1.5
Implantations / dam[a]	9.5 ± 2.0	9.3 ± 3.2	10.0 ± 2.7	10.7 ± 2.7
Resorptions / litter[a]	0.4 ± 0.7	0.7 ± 1.0	1.1 ± 2.3	0.8 ± 1.7
Number of litters with resorptions	7	6	8	7
Live fetuses / litter[a]	9.1 ± 1.9	8.7 ± 2.9	9.1 ± 3.4	9.9 ± 3.3
Fetal body weight(g)[b]	3.3 ± 0.1	3.1 ± 0.2	3.2 ± 0.4	3.1 ± 0.4

[a] Mean ± SD.

[b] Mean of litter mean ± SD.

TABLE 2

REPRODUCTIVE FINDINGS IN RATS TREATED WITH NDFDA ON DAY 12 OF GESTATION

	NDFDA (Mg/Kg) DAYS 12 - 20			
	Vehicle control	10	20	30
Maternal weight gain(g)	48.5 ± 7.0	52.3 ± 5.5	46.0 ± 15.3	29.5 ± 16.1 [c,f]
Number of litters	18	16	23	20
Corpora lutea / dam[a]	11.8 ± 1.6	11.3 ± 1.1	11.8 ± 1.4	10.8 ± 1.2 [d,f]
Implantations / dam[a]	10.5 ± 2.0	10.8 ± 1.1	10.2 ± 2.2	9.6 ± 2.3
Resorptions / litter[a]	0.2 ± 0.4	0.4 ± 0.6	0.2 ± 0.4	1.0 ± 1.4 [d,f]
Number of litters with resorptions	3	6	5	9
Live fetuses / litter[a]	10.3 ± 2.0	10.4 ± 1.1	9.8 ± 2.3	8.4 ± 2.6 [c,f]
Fetal body weight(g)[b]	3.2 ± 0.2	3.3 ± 0.1	3.1 ± 0.2	2.9 ± 0.4 [e,f]

[a] Mean ± SD.

[b] Mean of litter mean ± SD.

[c] Significantly different from the control value by the T-test, $p < 0.001$.

[d] Significantly different from the control value by the T-test, $p < 0.02$.

[e] Significantly different from the control value by the T-test, $p < 0.002$.

[f] S^2 is a pooled estimate of the population variance ($\hat{\sigma}^2$), based on the s of both samples combined.

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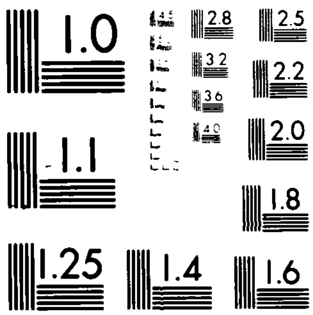

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 3

INCIDENCE OF FETAL MALFORMATIONS AMONG FETUSES FROM RATS GIVEN NDFDA

	NDFDA (Mg/Kg) DAYS 9 - 20				NDFDA (Mg/Kg) DAYS 12 - 20			
	Vehicle control	5	10	15	Vehicle control	10	20	30
External examination[a]	209(23)	130(15)	172(19)	188(19)	186(18)	166(16)	225(23)	169(20)
Soft tissue examination[a]	105(12)	65(7)	86(10)	94(9)	93(9)	83(8)	113(11)	84(10)
Skeletal examination[a]	104(11)	65(8)	86(9)	94(10)	93(9)	83(8)	112(12)	85(10)
External examination[b]								
microphthalmia	0(0)	1(1)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
Soft tissue examination[b]								
undescended testis	1(1)	1(1)	0(0)	0(0)	1(1)	0(0)	0(0)	4(2)
displacement of testis	0(0)	1(1)	0(0)	0(0)	1(1)	0(0)	0(0)	0(0)
Skeletal examination[b]								
bipartite sternebrae	0(0)	0(0)	0(0)	1(1)	4(3)	2(1)	2(2)	4(4)
split centrum	4(2)	3(2)	0(0)	0(0)	0(0)	0(0)	3(3)	2(2)
Total malformed	5(3)	6(5)	0(0)	1(1)	6(5)	2(1)	5(5)	10(8)

[a] Number of fetuses(number of litters) examined.

[b] Number of fetuses(number of litters) affected .

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FINAL REPORT

THE RESPONSE OF REINFORCED CONCRETE STRUCTURES TO NEAR FIELD EXPLOSIONS

Prepared by:	Dr. T. Michael Baseheart
Academic Rank:	Associate Professor
Department and University:	Civil Engineering Department University of Cincinnati
Research Location:	Engineering and Services Center/RDCS, Tyndall AFB, FL.
USAF Research Colleague:	Major Steven Hawn

Date:	September 5, 1980
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THE RESPONSE OF REINFORCED CONCRETE STRUCTURES TO NEAR FIELD EXPLOSIONS

by

T. Michael Baseheart

ABSTRACT

This investigation is a study of the response of buried reinforced concrete slabs that are subjected to high intensity, near field conventional explosions. A review of numerous experimental test reports revealed significant differences among test specimens, their restraint and loading conditions, and the interpretation of breach conditions. From these reports, the various failure mechanisms and their relationship to scaled breach distances are documented. This information is then used to evaluate an existing empirical design procedure. The extent to which existing analytical techniques are available to investigate this problem is also discussed. Recommendations for further experimental and analytical research on this subject are presented.

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In particular, the advise and assistance of Major Steve Hawn, Special Projects Branch Chief, is gratefully acknowledged. The author is also pleased to recognize Capt. Paul Rosengren for his collaboration.

I. INTRODUCTION

The ever increasing ability of weapons delivery systems to pinpoint their target has prompted survivability analysts and designers to upgrade the resistance capacity of protective structures. A hardened structure, which is typically a system that includes a shallow buried reinforced concrete structure covered by protective layer(s) of soil, concrete burster slab, rock rubble, etc., is required to provide protection against the very high overpressure from the near field, high energy explosion of conventional (non-nuclear) weapons. The inherent strength, stiffness and stability of boxlike structures makes them suitable for use in such a system. The present project is concerned with the dynamic response of reinforced concrete slabs, the major structural element of boxlike structures.

Conventional weapons detonated near a shallow-buried structure result in a rapidly attenuating, short duration pressure pulse, which is in sharp contrast to the well documented long duration shock front associated with nuclear explosions. As with the loading effects of the later, the design loading for conventional weapons can not be precisely documented. The design data will of necessity be essentially empirical, consisting of a combination of actual field measurements and theoretical results for hypothetical conditions. At present, a well-defined loading procedure is not available for analytical investigations.

Recently, experimental testing[3,4,5,6,7,8] has been performed in an effort to better define the characteristics of underground, non-nuclear explosions, and their effects on underground structures. These model tests provided much needed information about structural failure of reinforced concrete slabs and the in-structure environment to which the personnel, equipment, weapons, etc. would be subjected. The present project is limited in scope to the investigation of reinforced concrete slabs for failure loadings, along with their respective failure mechanism, due to high intensity, near field conventional explosions.

The presently available design procedure for determining the breach resistance of reinforced concrete slabs is based on the results of some of these model tests. The design procedure involves the use of the following empirical equation for the determination of the scaled

breach distance (λ) for a slab;

$$\lambda = \frac{R}{W^{1/3}} = 0.038\left(\frac{t}{L}\frac{t}{W^{1/3}}\right)^{-0.88} \qquad (1)$$

The equation was the result of a regression analysis applied to the data arranged to give the least scatter of the test data. Additional experimental data now available is to be included in the data base and then compared with the scaled breach distance predictions from equation 1. Comments regarding the ability of this equation to predict breaching will be made later in this report. In addition to providing for the immediate need of the design profession, the results of the model tests provide the basis for distinguishing the different modes of failure for reinforced concrete elements subjected to progressively more severe blast loadings.

Examination of photographs of failed test specimens over the suggested range of applicability of equation 1 indicate that the modes of failure for the slabs are widely varied. In order to better understand the fundamental behavior involved in the failure reponse of these ductile structural elements (under-reinforced slabs) containing brittle material (concrete), the following investigation procedure is suggested:

First, identify the different failure modes;

Second, distinguish the controlling parameters for each mode; and

Third, establish means of predicting failure conditions.

Due to recent physical testing, considerable experimental data is available to answer some of these basic questions about slab response. This information is organized and presented in a later section of this report.

This experimental data, which provided the basis for the empirical design equation given previously, also yielded the physical evidence necessary to suggest appropriate analytical models. For example, a recently developed digital computer code, CONCRE, was developed in response to the "plastic hinge" failure mechanism exhibited by the test specimens of reference 5. However, CONCRE is not appropriate for predicting response for a scaled distance sufficiently close to the member to cause material failure directly due to the extremely large intensity of the blast load (i.e. crushing of concrete, spalling). Unfortunately,

analytical stress models are not presently available to either adequately discribe the transfer of stress or to model all the failure conditions for reinforced concrete systems. The scope of the problem described in this introduction and the interaction of its components is summarized simplistically in Figure 1.

II. OBJECTIVES

The main objective of this project was the investigation of the failure response mechanisms of buried, reinforced concrete slabs subjected to high intensity, near field, conventional explosions, with the specific intent to:

(1) document the various failure mechanisms and their relationship to experimentally determined scaled breach distances,

(2) evaluate the applicability of the existing empirical procedure to model the additional test data found as part of the project, and

(3) investigate the applicability of existing analytical techniques and computer codes to describe the failure mechanisms.

This information provides a base on which future experimental and analytical work can be planned.

III. DOCUMENTATION OF FAILURE MECHANISMS

A review of numerous experimental test reports revealed significant differences among test specimens, their restraint and loading conditions, and the interpretation of breach loading conditions. The later is to be expected considering the different failure modes possible for reinforced concrete slabs that are subjected to blast pressures that range in magnitude from slightly above the static collapse load to several times larger than f'_c, the statically determined cylinder strength of concrete. Therefore, no attempt is made to arbitrarily define breach conditions. Rather, test specimens that sustained severe damage are classified according to their apparent mode of failure.

The failure test data used in this report is given in Tables 1 and 2. The information in Table 1 was used in reference 5 to obtain the previously stated empirical breach equation, while Table 2 contains

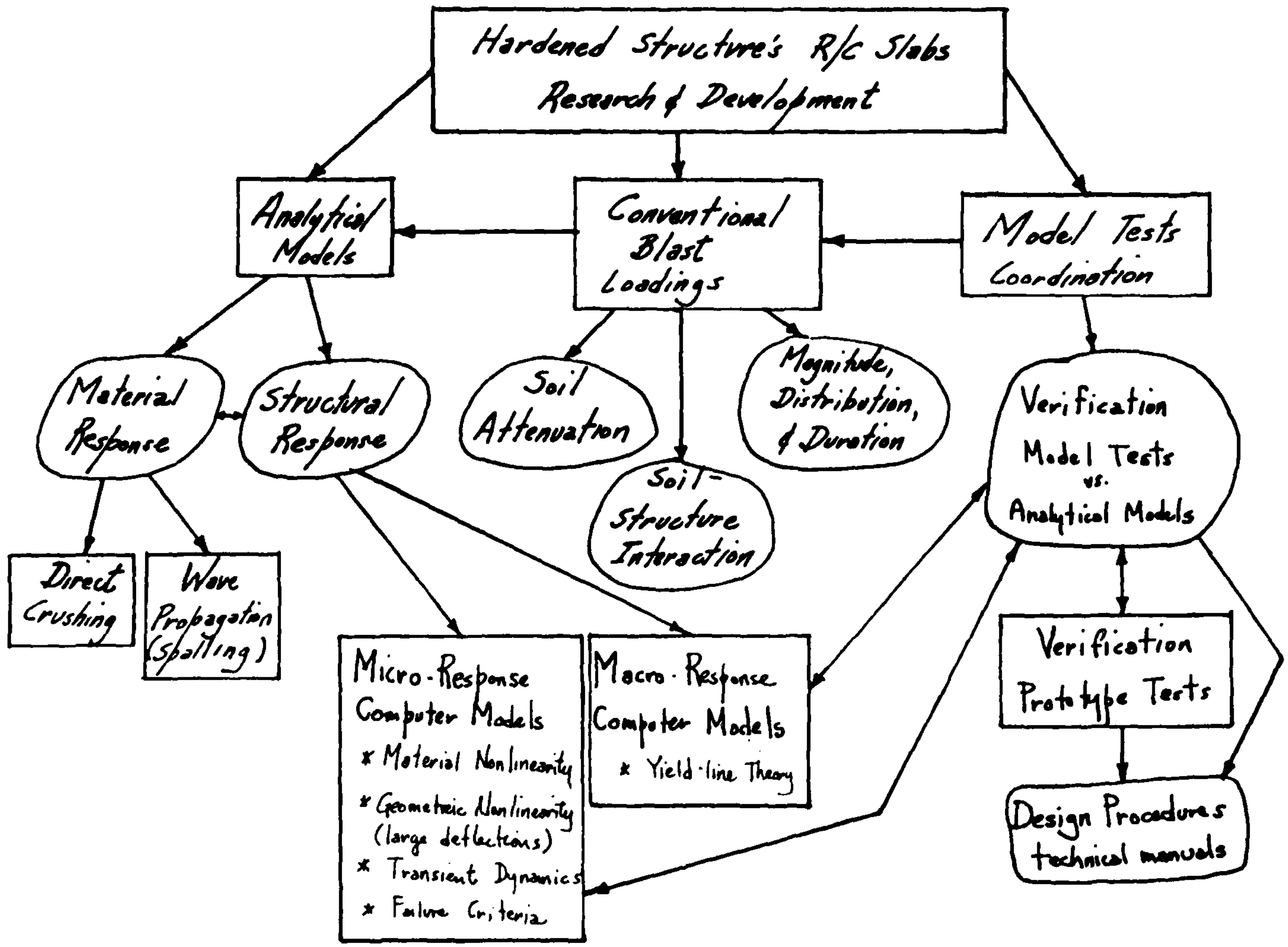

Figure 1. Interaction of Components of Slab Investigation

additional test data presently available. From an examination of the test data and photographs of these specimens, the following failure mechanisms are delineated based on the type and degree of damage:

(1) Yield Line, without concrete degradation,

(2) Yield line, with concrete degradation,

(3) Membrane, with severe spalling or scabbing,

(4) Direct concrete crushing and spalling, with membrane net,

(5) Shear, and

(6) Overbreach.

These assumed failure response mechanisms have the following characteristics.

Yield Line, without concrete degradation. This mechanism is characterized by plastic hinge formation at points of maximum flexural stress with the sections of the member between hinge lines remaining essentially intact. Under-reinforced concrete elements possess the necessary ductility for its reponse to be idealized by a rigid, perfectly plastic, constitutive relationship. This flexural failure is characterized by crushing of the concrete along the yield line in the flexural compression zone of the crossection. The depth of this concrete loss is not excessive because concrete slabs are usually considerably under-reinforced. With tied compressive reinforcement present, the member continues to respond in this flexural mode until fracture occurs due to excessive straining of the tension reinforcement. For severe overloads, the compressive reinforcement may also fracture, resulting in total disengagement between hinges.

Yield Line, with concrete degradation. In addition to the previously described flexural failure associated with the formation of the plastic hinge(s), concrete failure occurs directly due to the intensity of the blast pressure.

Membrane, with severe spalling or scabbing. When the edges, or at least the corners, of a slab are restrained against in-plane motion, lateral deflections beyond a certain level ($\Delta \geq 0.3t$) are accompanied by stretching of the middle surface[1]. As the magnitude of the maximum deflection increases, the resulting membrane force can significantly aid or even predominate in carrying the lateral loads. The final deflected shape of reinforcing steel in test specimens failed with this mechanism is con-

sistent with the shape observed for pure membranes subjected to distributed loads. The analytical and experimental results of reference 16 support the concept of this membrane type failure response for thin, fixed-edge flat plates subjected to explosive pressure loadings. Spalling, which is caused by the shock pressure of a blast being transmitted through an element, results in a tension failure in the concrete normal to its free surface. Scabbing is also a tensile failure of the concrete, but is associated with the large strains in the reinforcement at the later stages of ductile response of a reinforced concrete element. The velocities of scabbed fragments of concrete are lower than the velocities of spalling fragments.

Direct concrete crushing and spalling, with membrane. The following description from reference 13 of the response of a member to a contact explosion also describes the mode of failure under consideration. Near the point of detonation, the magnitude of the compressive pulse is sufficient to crush the concrete material. The pulse decays rapidly as it propagates through the member until no additional crushing is possible or the structure is breached. If the later does not occur, a compression wave is reflected by the inner surface as a tension pulse wave. If the tensile strength of the concrete is exceeded, rupture will occur and the spall will fly off in response to the trapped momentum. Additional ejection of crushed and spalled material occurs as the tension wave propagates back to its point of detonation. The flexural capacity of the member is lost, leaving only the membrane capacity of the reinforcing net.

Shear. This is a catastrophic failure mode in which there is very little evidence of flexural behavior. The affected area of wall is typically blown into the structure nearly intact, with boundaries showing direct shear failure, rather than diagonal tension failure.

Overbreach. Catastrophic damage is obvious, with concrete disentegrated and blown away. The reinforcing steel does not span the opening and is in disarray.

The experimental breach data is plotted in Figure 2 with each data point symbol indicating the failure mechanism for that test specimen. Figure 3 shows the different slab support configurations used in the various testing programs, while Figure 4 relates this factor to

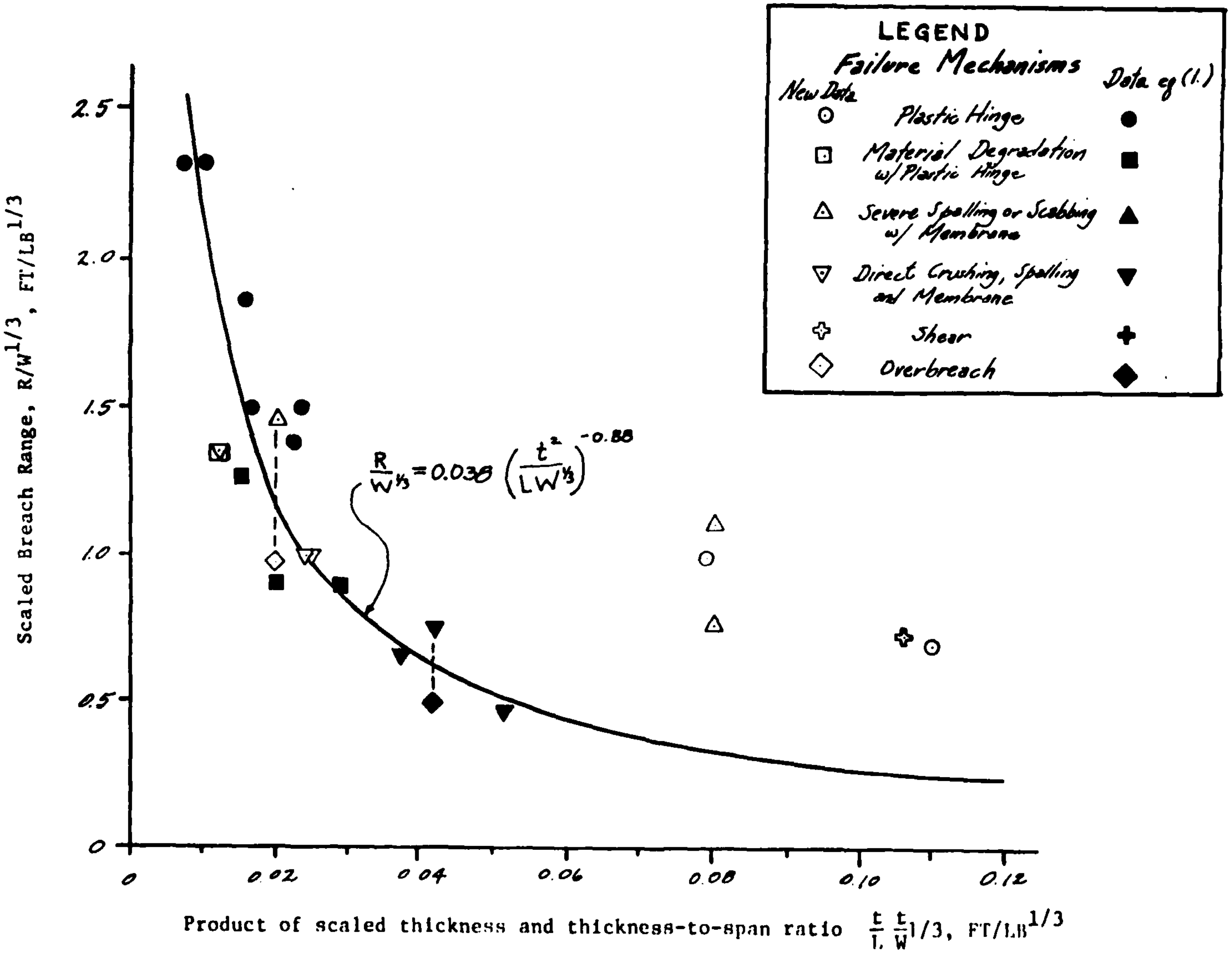

Figure 2. Failure Mechanisms for Blast Loadings

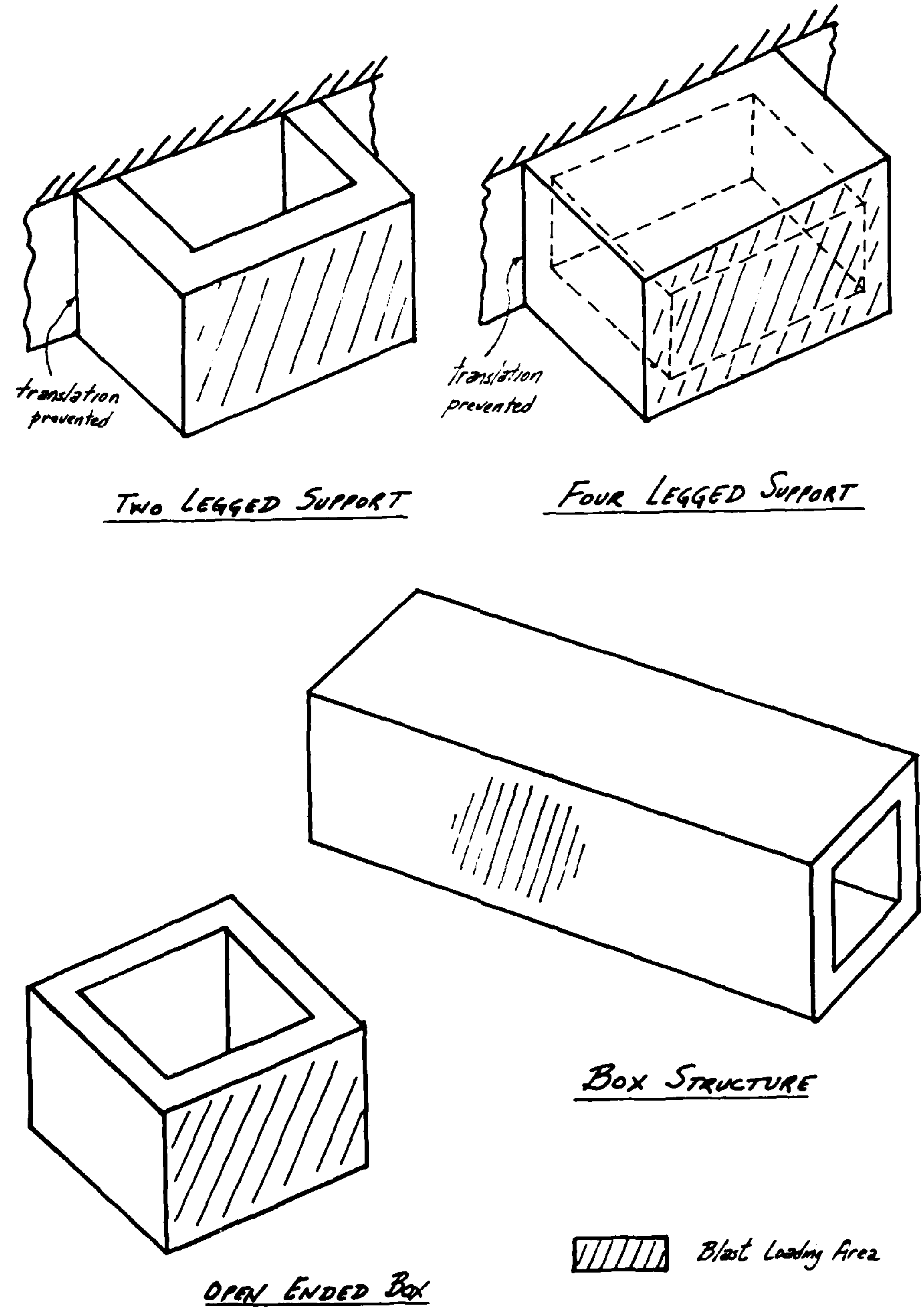

Figure 3. Support for Slab Specimens

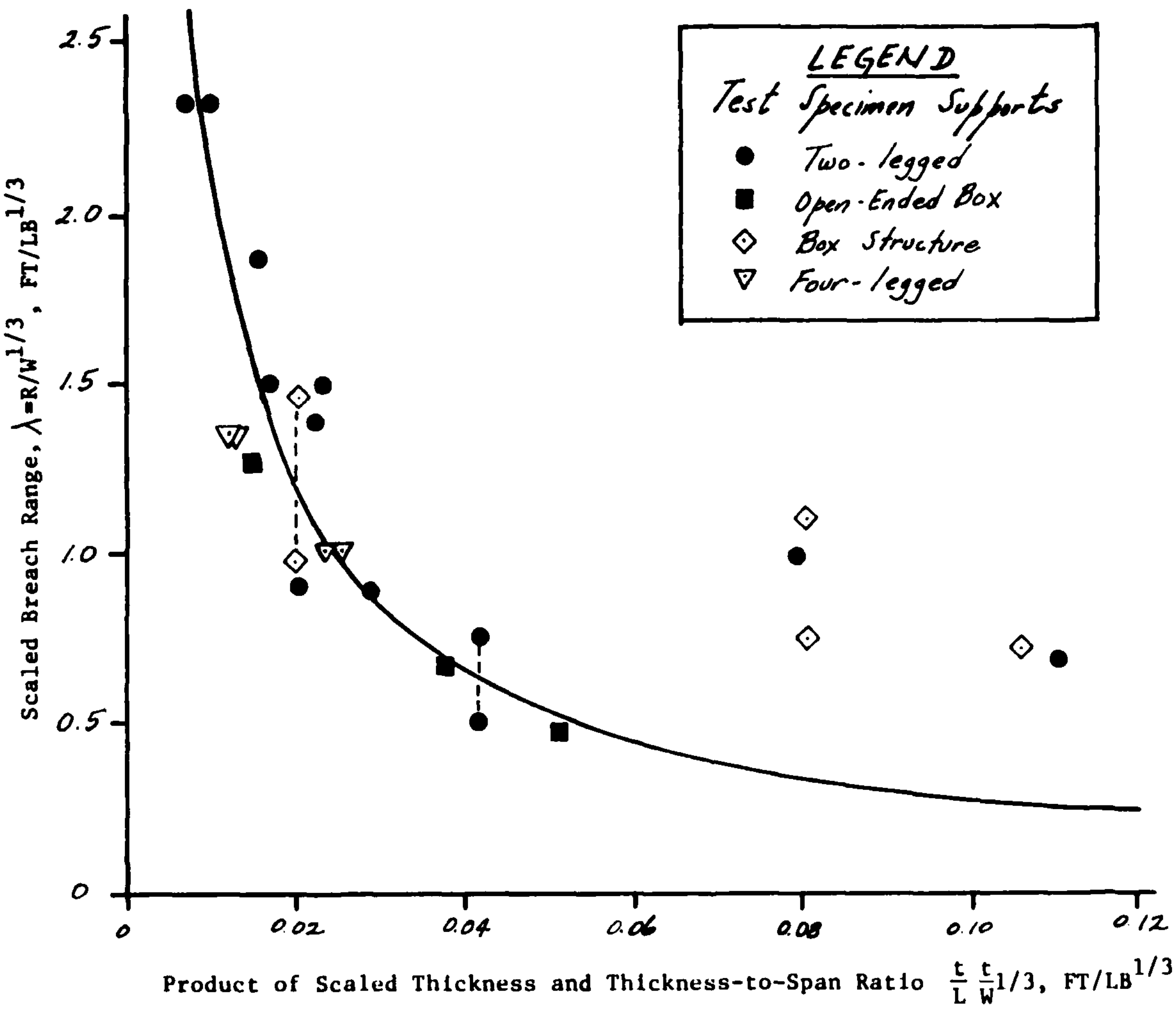

Figure 4. Test Specimen Support Conditions for Failure Loadings

the scaled breach distance for each test specimen. Several observations can be made from a consideration of these figures

Except for one test, the data for $\lambda \gtrsim 1.4$ consists entirely of the results from slabs supported on two legs. The slabs in these tests fail in flexurel through the formation of yield lines. The author observed that because of the lack of in-plane translation restraint on the slab, the membrane capacity of the slab is not utilized as it might be in a real box structure. The distinctive yield line (plastic hinge) is not observed to form in any of the test specimens which are provided in-plane restraint against translation by their supports.

Tables 1 and 2 indicate that the majority of the test specimens contain considerably less steel reinforcement than one would expect to find in actual hardened structures. No reference that attributes this reduced reinforcement value to model scaling was found. While conservative, the use of steel ratios significantly less than that of actual structures should have a pronounced effect on the specimens with the larger breach loading distances where structural member response, rather than direct crushing of the concrete material, is the primary cause of failure.

For scaled breach distances less than 1.4 there appears to be direct material degradation present due to the initial intensity of the blast pressure on the restrained test specimens. The two test specimens in this range that did fail without direct material crushing are unrestrained two-legged test specimens. These two specimens also contain a steel ratio $\rho = 0.0025$ for the tensile reinforcing steel in one direction. This definition for steel ratio, consistent with conventional reinforced concrete practice, is equal to one-fourth of the amount reported in reference 4 as the volume of steel in the specimen. This minimal amount of reinforcement, equivalent to what is normally considered an amount of steel simply for temperature and shrinkage control, probably accounts for the unexpected yield line failure mechanism in the high intensity range of scaled breach distances. It should be pointed out that the yield line failure mechanism would appear essentially the same as a modulus of rupture type failure typical of a concrete flexural member that is effectively unreinforced.

There is insufficient breach data presently available to support the use of the empirical equation previously described for values of $t^2/LW^{1/3}$ greater than approximately 0.05. The original proposers[5] of this equation apparently had this limitation in mind; however a recent publication[3] has suggested its applicability over a range twice the value stated above. The imminent failure and breach data plotted in Figure 2 illustrates the need for additional tests before this extended range can be supported.

IV. LOADING FUNCTIONS

For conventional static and dynamic reinforced concrete analysis and design, the effects of the intensity of the loading applied transverse to a flexural element are usually considered negligible. Meanwhile, the magnitude of the in-plane stresses which result from the member displacement-deformation compatibility requirements are critical in determining the capacity of the member. The experimental results in the previous section of this report demonstrate that this is not necessarily the case for members subjected to near field blast loadings. A discussion of analytical procedures to come later in this report also requires the consideration of blast load parameters on buried structures.

The experimental tests that generated the breach data discussed previously also yielded valuable data on free field pressures in soils and interface pressures on buried slabs. These tests provide the data necessary to perform the empirical fits for peak pressures (P_o) from buried charges using the approximate formula of the form

$$P_o = k\lambda^{-n}, \tag{2}$$

where k is the soil constant. The pressure which is exerted on a buried protective structure may be greater or less than the free earth pressure, depending upon the soil-structure interaction. The results of the process from references 2, 3, 5, and 12 are plotted on Figure 5. For emphasis, data points from references 4 and 5 for scaled distances that produced measured peak pressures larger than 10,000 psi are also plotted

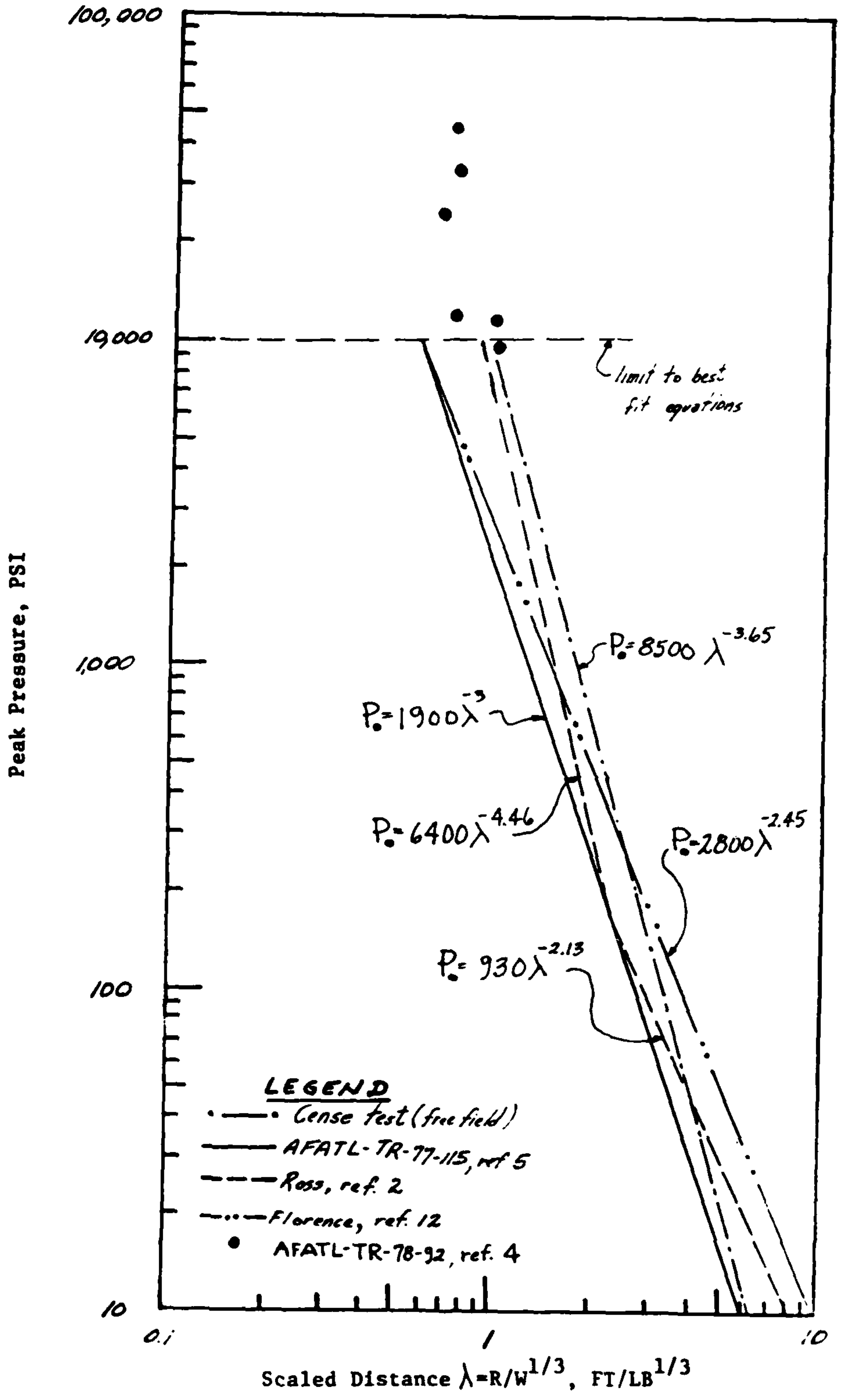

Figure 5. Peak Pressures vs. Scaled Distance

individually in the graph. The author realizes that there is a wide range of different physical conditions under which these measurements were recorded. However, the figure does indicate the magnitude of the range of peak pressures possible for a particular scaled distance from the explosion.

In addition to peak pressure magnitudes, the blast pulse shapes and duration are obviously important. Consistent with current literature, the overpressure at a specific distance from the center of the explosion is assumed to decay in an exponential manner with time. The expression for this overpressure can be written[2] as

$$P = P_o\left(1 - \frac{t}{t_o}\right)e^{-\frac{\alpha t}{t_o}} \qquad (3)$$

where t_o is the duration of the positive phase of the duration, and α is the time decay constant. When the conditions are such that the element responds to an impulse, the maximum response depends on the area under the pressure-time curve. In this case, the magnitude and time variation of the pressure are not important in the determination of the structural response, assuming no direct material degradation takes place.

For near field explosions, there is considerable uncertainty regarding the soil-structure interaction that takes place. The effect of wave transit times through different soils can have an effect on the temporal parameters, as well as the spatial distribution of loading on the element.

V. DYNAMIC ANALYSIS AND DESIGN

From the point of view of practical design, the undamped equivalent single degree of freedom (SDOF) model for beams and slabs has been used for the past couple of decades. The method requires that both the structure and loading be idealized in some degree. When considering the failure response of an element, the model typically has a bilinear resistance function and failure is usually defined in terms of a ductility. Ductility ratio μ is the ratio of the maximum deflection to the elastic limit deflection.

The SDOF model is used here simply to illustrate the difference in the resistance required from a slab when subjected to a nuclear loading, as compared to a conventional non-nuclear blast. In order to accomplish this task, limiting cases of inelastic response with idealized load functions are considered.

For the nuclear blast, the assumption is made that the duration of the load is so long that the change in the instantaneously applied load F up to the time of maximum response is negligible. From a consideration of work done by this force, reference 9 determines the required resistance of the slab to be

$$\text{required } R_m = F\left(\frac{1}{1-\frac{1}{2\mu}}\right) \tag{4}$$

Equation 4 indicates that the minimum value of the required strength R_m is equal to the magnitude of the applied blast force. This minimum value can only be achieved when large plastic deformations are allowed. At the other extreme, the conventional non-nuclear explosion involves an instantaneously applied short duration load, F. Considering the loading to be a pure impulse, the following equation is determined[9] for the required resistance of the member

$$\text{required } R_m = \frac{i\,\omega}{\sqrt{2\mu-1}} \tag{5}$$

where i = impulse = area under load curve, and

ω = natural circular frequency of the member.

A significant observation to be made from equation 5 is that for very large plastic deformations, the required strength of the member R_m approaches zero. While equations 4 and 5 are for idealized load durations which are extremely long or short, they do provide an insight into the difference in the required strength of a member for nuclear as compared to conventional blast loadings.

The question of the ability of undamped SDOF models to adequately describe the dynamic structural response of slabs subjected to conventional blast loadings was addressed recently in reference 3. The fol-

lowing conclusions based on the comparison of analytical results and experimental data are presented in that publication. First, while most failure analysis methods currently define failure in terms of ductility, the determination of a value for the failure ductility is very difficult. Therefore, ductility is a poor measure of failure. Second, while undamped SDOF models significantly overpredict the measured response, the improved analysis obtained using a damped model depends significantly on the initial stiffness of the resistance function. Improved analytical methods for predicting failure conditions are needed.

In response to the yield line failure mechanism present in the reinforced concrete test specimens of reference 5, two researchers working independently responded with the observation that this was the same type of "moving hinge" failure mechanism observed in thin metal beams subjected to uniformly distributed impulsive loads[16]. Both investigators used the assumption from static yield line analysis procedure[19] in that the material behavior is considered rigid-perfectly plastic. This is reasonable when one considers that the failure deflections are extremely large in comparison with the elastic deflections. Tensile membrane forces are not considered since axial restraint is not provided by the supports in the test specimens modeled. Whether this is consistent with the actual conditions found in real structures is questionable. Of the two works, the solution procedure of reference 2 is more suitable for research efforts because it has been computer coded. This program, CONCRE, allows some control over the temporal and spatial loading parameters. The developer of the procedure emphasized that the analysis is limited to blast pressures that exceed static collapse loads, but are less than the pressure that causes the concrete to fracture and separate from the reinforcing elements.

No additional special purpose analytical procedures or computer codes specifically formulated for the limited scope of the stated problem was discovered. Therefore, attention was directed to locating existing general purpose finite element computer codes that could be used to model the problem. A description of some computer codes that could prove appropriate is contained in Table 3. No effort to determine the strains, displacements, etc. generated by a near field conventional blast loading on a reinforced concrete element using these codes was undertaken during this project.

Experimental results point out that the behavior of the slab is much more complex than can be explained by the yield line theory which is currently widely used for analysis purposes. In order to examine the effects of local pressure intensity on material response, the soil-structure interaction, the effects of defects on performance, stress wave propagation, membrane response, etc., the use of finite element techniques or sophisticated energy methods will most certainly be necessary. The analytical investigation should be limited to the analysis of one-way slabs in order to concentrate the effort on the understanding of fundamental material response. For member response to pressures less than that necessary to break up the concrete locally, the influence of membrane action on the member's response should be investigated analytically. For the larger pressures due to very near field explosions, the analytical study of the blast response of concrete should be initiated in order to explain the fundamental behavior of the material in the member. This information would help to answer questions such as the following: While the scaled thickness of a physical test specimen is intended to model the flexural response of the structural element, does it model satisfactorily the degradation of the member due to stress propagation or the direct crushing caused by the intensity of the blast pressure?

Report / Test No.	Support Type	t (in)	ρ	L (ft.)	f_c (ksi)	f_y (ksi)	R (ft)	W (lb.)	λ (ft/lb$^{1/3}$)	Failure Mode	$\frac{t}{L}\frac{t}{W^{1/3}}$ (ft/lb$^{1/3}$)	L/t	Explosive Type	Explosive Shape
AFATL-TR-77-115														
3	1	4.0	0.0050	3.33	>6.0	>47.5	~~2.0~~ 1.5	4.64	~~1.20~~ 0.90	2	0.0200	10.0	C-4	
5	1	4.0	0.0050	3.33	>6.0	>47.5	3.0	7.94	1.50	1	0.0167	10.0	C-4	
7	1	4.0	0.0050	3.33	>6.0	>47.5	4.0	10.00	1.86	1	0.0155	10.0	C-4	
9	1	4.0	0.0050	2.33	>6.0	>47.5	~~2.0~~ 1.5	4.64	~~1.20~~ 0.90	2	0.0286	7.0	C-4	
11	1	4.0	0.0050	2.33	>6.0	>47.5	3.0	7.94	1.50	1	0.0238	7.0	C-4	
13	1	4.0	0.0050	2.33	>6.0	>47.5	3.0	10.00	1.39	1	0.0222	7.0	C-4	
17	1	4.0	0.0050	1.33	>6.0	>47.5	1.0	7.94	0.50	6	0.0418	4.0	C-4	
19	1	4.0	0.0050	5.33	>6.0	>47.5	5.0	10.00	2.32	1	0.0097	16.0	C-4	
20	1	4.0	0.0050	5.33	>6.0	>47.5	7.0	27.00	2.33	1	0.0069	16.0	C-4	
AFATL-TR-77-1 Vol. II														
10	2	8.0	0.0063	4.00	>6.0	Grade 40	1.0	10.00	0.46	4	0.0516	6.0	C-4	
15	2	8.0	0.0063	4.00	>6.0	Grade 40	2.0	27.00	0.67	4	0.0370	6.0	C-4	
21	2	4.0	0.0050	4.00	>6.0	Grade 40	2.0	4.00	1.26	2	0.0175	12.0	C-4	

Table 1. Experimental Failure Data for Equation 1.

Report / Test No.	Support type	t (in.)	ρ	L (ft.)	f_c (ksi)	f_y (ksi)	R (ft.)	W (lb.)	λ (ft/lb$^{1/3}$)	Failure Mode	$\frac{t}{L}\frac{t}{W}$ (ft/lb$^{1/3}$)	L/t	Explosive type	Explosive shape
WES-TR-SL-80-1														
3-3C	4	5.6	0.0089	4.0	6.5	>70	4.0	21.0	1.45	3	0.0200	8.6	TNT	sph.
5-3C	4	5.6	0.0089	4.0	6.5	>70	2.7	21.0	0.98	6	0.0200	8.6	TNT	sph
8-3D	4	13.0	0.0085	4.0	6.5	>70	2.0	21.0	0.73	5	0.1060	3.7	TNT	sph
AFATL-TR-78-92														
17	1	8.0	0.0025	2.8	>6.0	75	1.0	3.0	0.69	1	0.110	4.2	C-4	
19	1	8.0	0.0025	2.8	>6.0	75	2.0	8.0	1.00	1	0.079	4.2	C-4	
3	3	4.0	0.0050	2.33	>6.0	75	2.0	8.0	1.00	4	0.024	7.0	C-4	
6	3	4.0	0.0050	2.33	>6.0	75	4.0	27.0	1.33	4	0.016	7.0	C-4	
8	3	4.0	0.0050	2.33	>6.0	75	4.0	27.0	1.33	2	0.016	7.0	C-4	
10	3	4.0	0.0050	2.33	>6.0	75	2.0	8.0	1.00	4	0.024	7.0	C-4	
AFATL-N-77-8														
1	4	12.0	0.0092	4.00	4.0	Grade 40	3.50	31.0	1.11	3	0.080	4.0	AFX 108	cyl. cased
3	4	12.0	0.0092	4.00	4.0	Grade 40	2.42	31.0	0.77	3	0.080	4.0	AFX 108	cyl. cased
AFATL-TR-77-115														
16	1	4.0	0.0050	1.33	>6.0	>47.5	1.5	7.94	0.75	4	0.042	4.0	C-4	

Table 2. Additional Failure Test Data

TABLE 3 Computer Codes

Program Name	Program Description
SAMSON[17]	A two dimensional finite element code developed for the dynamic stress analysis of non-linear media structure problems. It is based on small strain theory and is applicable to axisymmetric and plane bodies with arbitrary material properties. The code has the capability to treat sliding/debonding interfaces. Constitutive laws for a cracking composite material, such as reinforced concrete, are available as well as the ability to add other material constitutive laws as needed.
SINGER[18]	The function of the code is to predict the behavior of plane skeletal reinforced concrete structures in their environments. Of primary interest is the transient nonlinear response including element failures and structural collapse. The structure is represented by a discrete model composed of line elements that admit geometric and physical nonlinearities; they can predict the behavior of reinforced concrete members subject to axial and flexural distortions up to failure. The state of an element is characterized by its internal energy.
SAP V (SAP IV)	A structural analysis program for static, free vibration, transient, or spectral response of large three-dimensional systems. The structural systems to be analyzed may be composed of combinations of nine different structural elements, including isoparametric membranes and solids. Especially recommended for seismic analysis.
NONSAP	NONSAP solves static and dynamic, linear, and nonlinear problems. The nonlinearities may be due to material nonlinearity, in which case elastic, hyperelastic, and hypoelastic material behavior may be considered, or the nonlinear effects may arise from large displacements and large strains. The isoparametric finite element discretization used is shown to be very effective for general application.

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FINAL REPORT

INCENTIVES FOR DEFENSE INDUSTRY INVESTMENT

Prepared By:	F. Thomas Bear, Ph.D.
Academic Rank:	Associate Professor of Finance
Department and University:	Department of Economics and Finance Western Carolina University
Research Location:	Air Force Business Research Management Center Headquarters USAF (AFBRMC/RDCB) Wright-Patterson AFB, Ohio
USAF Research Colleague:	Major Robert F. Golden

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<u>Incentives for Defense Industry Investment</u>

by

F. Thomas Bear, Ph.D.

<u>ABSTRACT</u>

A rapid escalation in the cost of weapons systems and materiel has been of increasing concern to the Department of Defense for several years. Higher prices have led to a reduction in the quantity of weapons and materiel that can be purchased. Several studies, including the Air Force Systems Command effort entitled Manufacturing Technology Investment Strategy (Payoff '80) have looked at these problems. Suggestions have been made that greater investment in modern manufacturing equipment by defense contractors could result in lower costs and higher productivity for weapons and materiel. Recent studies of defense industry investment and profits are reviewed. Numerous possible incentives for defense industry investment are identified. A questionnaire is developed to obtain input from defense contractors as to the value of suggested incentives and to elicit their ideas for other incentives that have the potential to generate significant investment in the defense industry.

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I. Introduction

The Air Force Systems Command Manufacturing Technology Investment Strategy Task Force conducted a study, "Payoff '80," during 1980. This study was designed to determine methods to encourage the increased use of advanced manufacturing technology by defense contractors. It is desirable to increase the use of manufacturing technology in order to slow the rapid escalation in the cost of weapon systems. Appropriate use of modern technological equipment can be an effective means to increase productivity in manufacturing operations. Although the formal study, "Payoff '80," has been completed, there is a continuing interest in investment strategy at the Air Force Systems Command.

The Business Team of the Payoff '80 organization was established to accomplish the following objectives:

(1) Encourage defense contractors to invest in advanced manufacturing technologies.

(2) Determine means to evaluate the benefits of investments that are made in manufacturing technology.

(3) Establish means for transferring technology throughout industry and Government.

Problem

Conversations were held with several members of the Payoff '80 Task Force to determine what had been accomplished and areas requiring further effort. These conversations disclosed that further information about how defense contractors make investment decisions is needed. Particular interest was expressed in the decision making process between investments relating to commercial business and those relating to defense business. Special interest was expressed in the following questions:

(1) What considerations are used by corporations developing investment strategies for commercial/defense investments? Can these considerations be rank ordered?

(2) How important is return on investment (ROI)? What is considered the minimum acceptable ROI? Is the minimum ROI required for investments in equipment related to defense business different from the ROI required for investment in equipment related to commercial business?

(3) What criteria are used to evaluate investments in defense related manufacturing equipment? Do these criteria differ from those used for investments related to commercial investments?

(4) Have recently adopted methods of encouraging defense related investments been effective? (These methods include indemnification and changes in weights used to determine profits allowed on defense contracts to reflect investment.) What further incentives could be used to encourage manufacturers to invest in advanced technological equipment for defense work?

This study investigated past attempts to encourage defense contractors to increase their investment in manufacturing equipment. A questionnaire was developed to obtain information from defense contractors regarding the value of existing incentives and to obtain their input as to what incentives would most effectively stimulate defense industry investment.

II. Objectives of the Research Effort

The primary objectives of this research was to identify investment incentives that have the potential of encouraging defense contractors to increase their investment in manufacturing equipment for use in fulfilling defense contracts. Increased investment by defense contractors should reduce the cost of weapons systems and other materiel procured by DOD. Specific objectives of the research were:

(1) Identify investment strategies that should encourage defense contractors to increase their investment in manufacturing technology.

(2) Develop a means to evaluate the impact of proposed investment incentives on defense contractors.

III. Investment Incentives for Defense Contractors

The Department of Defense (DOD) has acknowledged that profit is essential to building and maintaining an adequate defense industrial base. The Defense Acquisition Regulations (DAR) state that profit should be used to stimulate defense contractors. Adequate profits are seen as leading to effective and economical contract performance. It is noted that low profits are not in the public interest and will not attract the best industrial performers to compete for defense contracts. According to the DAR, negotiations concerning profits should be directed towards encouraging effective performance, not minimizing profit.[1]

Recent changes to the DAR have been designed to encourage investment by defense contractors. Following "Profit '76" the guidelines were amended to allow additional profit for investment used for the contract. The DAR now states that new facilities and equipment should be given maximum weight in the determination of profit when:

(1) They are acquired primarily for use in defense business.
(2) They have a long service life.
(3) Alternative uses are limited.
(4) Total cost of the defense goods produced are reduced.[2]

Recent recommendations, regarding profit policy, arising from "Profit '76" and "Payoff '80" followed a number of studies that indicated that defense industry profits were not adequate to encourage defense contractors to invest in defense related plant and equipment. The Logistics Management Institute's 1967 review of defense industry profits suggested that several changes to DOD policy in the early 1960's had an adverse impact on defense contractor's profits. These changes included:

(1) Increased emphasis on price competition and less cost reimbursable contracting.
(2) A lower rate of progress payments.
(3) More emphasis on contractor supplied facilities as opposed to government owned facilities.

During this period contractor profits declined.[3]

A 1971 study of defense industry profits, conducted by the General Accounting Office found that profits on defense business were significantly lower than profits on comparable commercial business. At that time the rate of return on sales was over twice as much for commercial business as for defense related business. However, return on investment for defense business was not found to differ significantly from that of commercial business. Contractor investment for defense business was less than for commercial business because of progress payments and the use of government facilities for defense related business. It was noted by the GAO that capital requirements were not considered in negotiating defense contracts at that time (1971).[4] Rates of return on capital equipment were found to vary from a negative 78% to a return of 240%. Profits were based on costs, so lower costs meant that profits would be reduced. Unless there was competition for the contract there was no incentive for a defense contractor to reduce costs. Congressional hearings that resulted in the GAO study indicated that there was some interest in the idea of giving consideration to capital investment by the contractor in the determination of profit on defense contracts.[5] A study of defense industry profits by the Logistics Management Institute, published in March 1970 indicated that defense industry profits were lower than commercial business profits for 10 of the 11 years from 1958-68.[6]

The Air Force/Industry Manufacturing Cost Reduction Study of 1972 analyzed aircraft production with the purpose of reducing costs while retaining quality. A number of suggestions were made but they do not appear to have been very effective.[7]

Goodhue pointed out in a 1972 article, that basing profit on costs meant that capital investment would reduce return on investment. An investment in plant and equipment by a defense contractor had a potential double negative impact on profits as follows:

(1) If the investment resulted in lower costs, the profit allowed would be reduced.

(2) The increased investment created a larger base to determine the percentage of profit on investment.

Therefore, investment by a defense contractor in cost reducing equipment had the potential to significantly lower profits, both in dollars and as a percentage of sales, under regulations in effect during the 1960's and early 1970's. The recognition of this negative impact caused the DOD to attempt to identify means for allowing credit for investment as long ago as the late 1960's.[8]

Procurement of major defense systems is a long, complex, expensive system. Many years elapse between the concept of a new weapon until delivery. During this time there may be continuing technological changes.[9] These constant changes in technology can be a serious impediment to the goal of reducing the cost of weapons system. It means that, in effect, a contractor is producing a series of slightly different weapons systems over the period of the contract.

Bertrand suggested that corporations obtaining over 45% of their business from DOD were dependent on continuing defense contracts for survival. This could lead them to accept a lower return on investment in order to retain DOD business. These companies must conform to DOD requirements and incentives may be important to them. They are very sensitive to DOD policy.[9] Properly designed incentives could be effective with these corporations.

A very important factor in management investment decisions is present and expected future demand. Demand for military goods was very unstable in the 1967-74 period studied by Bertrand. Extreme shifts in demand occurred in brief periods of time. For example, ship procurement rose from $2.1 to $3.5 billion in constant dollars, while ammunition purchases declined from $2.2 billion to $1.3 billion over the same 1971 to 1973 time period. Seventy-one percent of low percentage defense contractors stated that commercial business was much more predictable than DOD business.[10] Bertrand's 1977 study for the Logistics Management Institute confirmed four previous LMI studies that indicated commercial business was more profitable than defense business.[11] In looking at investments companies want to see profitability and low risk. Risk is measured in terms of the stability of sales, profits, and cash flow. In order to make an investment in equipment that

would be seen as risky, it is necessary to see a high rate of return. In the case of the defense industry in the 1960's and 1970's we have seen two deterrents to investment:

(1) Profits were lower than those available on commercial business.

(2) Sales were unstable leading to an undesirable degree of risk.

A natural reaction to unstable sales is to avoid investing in equipment which requires a large investment that will not be recovered for many years. Instead a company will become labor intensive and hope to expand and contract its work force to meet changes in demand.

The Logistics Management Institute recommended five changes to procurement policy in 1976.

(1) The DOD should agree to purchase equipment used to increase productivity on defense contracts for the unrecovered cost if the contract is terminated.

(2) Multi-year contracts should be used by the department of defense.

(3) Fees should be awarded to defense contractors who come up with signficiant cost reductions.

(4) Cost savings on defense contracts should be shared with industry.

(5) More rapid depreciation should be allowed.[12]

Implementation of these recommendations would appear to be helpful in achieving the objective of encouraging investment by defense contractors. Some have been tried to a limited extent. For example, the Air Force recently awarded three-year ammunition contracts to two companies. General Slay, Commander of the Air Force Systems Command, called the contract a "milestone in the process of improving our way of doing business."[13]

Paulson pointed out in 1972 that DOD profit policy had as two objectives:

(1) To build an adequate defense industrial bases for national security.

(2) *To reduce the cost of weapons by encouraging industry to invest in modern equipment.*

In fact DOD policy at that time discouraged investment by defense contractors. Profits were based on costs and lower costs meant lower profits.[14]

In 1970 a committee of the Industry Advisory Council recommended that profit on defense contracts should be comparable to that on commerical business. It was suggested that profit should be based on management capability, technical skill, and capital investment. The recommendation was tested on a few sample contracts during 1970.[15]

A major DOD profit policy study was completed in 1976. The review of profits found that defense contractors profits were significantly lower than commercial profits. Return on sales and return on investment were both significantly lower for defense contractors. It was recognized that companies would not make investments in defense production facilities if there were significantly greater opportunities for profitable investment in commercial production facilities.[16]

The "Profit '76" study included a survey of financial executives of financial institutions that supply funds to business. Financial executives identified the chief problems of the defense industry as follows:

(1) Defense industry profits are inadequate for the risk involved.

(2) The principal risk is uncertainty, both of fulfilling current contracts and of winning future contracts.

(3) "Buying in" by some contractors and poor management.

(4) DOD policies and practices such as excessive management or policy changes, changes in specifications during production, and an adversary position toward defense contractors.

(5) Serious weaknesses among subcontractors.

In order to remedy these weaknesses the financial officers made a number of recommendations.

(1) Higher profits were needed.

(2) There should be a better balance between risk and reward.

(3) DOD needed better procurement planning.

(4) DOD should be more realistic when negotiating contracts.

(5) Multi-year funding is required.

(6) Disputes over contracts should be promptly and fairly settled.

(7) Interest costs should be an allowable expense.[17]

Policy recommendations from the Profit '76 Policy Group included:

(1) Recognize the importance of capital investment. Compensate contractors for capital used for defense contracts. Allow higher profits to compensate for the risk associated with capital investments specifically related to defense contracts.

(2) Emphasize effort and risk in the determination of profit.

(3) Recognize productivity on the current contract as a profit determinant. Include cost/performance incentives in the contract.[18]

General Marsh recognized the necessity of modernizing plant and equipment used for defense production if production costs were to be reduced. He stated that improvements could be made to government-owned plant and equipment, but that the prime objective was to encourage industry to make investments. General Marsh also suggested that some performance requirements for weapons systems may cost more than they are worth.[19]

Profit'76 recognized the importance of profit as an incentive to defense contractors, as numerous prior studies had. The report led to stated changes in profit policies. Subsequent events made it clear that these changes were not adequate to encourage significant investment in defense related manufacturing facilities. McCullough analyzed profits on defense contracts before and after "Profit '76" and found no measurable change. There was no indication that contractors had increased their investment in facilities.[20]

An Association of the U.S. Army study suggested that pressure from Congress and the Pentagon caused military buyers to drive hard bargains. The presence of 40,000 watchers evaluating contracts leads to hard bargaining

which in turn leads to low profits. Low profits and unstable business caused many corporations to drop military business.[21]

Voelker interviewed industry and government individuals involved in defense contracts to determine the impact of "Profit '76" guidelines on profit. Various government sources indicated that profit increased, decreased, or stayed the same. Industry sources indicated that there was little change in profits. Overall the study indicated that profit changes were not adequate to encourage additional investment.[22]

Jacques Gansler pointed out in a Harvard Business Review article that the reduced defense expenditures following the Vietnam War had some unique features, not found in other post-war reductions.

(1) Defense procurement, in constant dollars, fell to the lowest point since the early 1950's.

(2) Foreign military sales were becoming essential to the U.S. defense industry.

(3) A major potential adversary, the Soviet Union, had established a quantitative edge in most equipment and had narrowed the gap in sophistication.[23]

Gansler also pointed out another cost inflator implicit in a fluctuating market. Numerous studies had pointed out that a fluctuating market discourages investment in technological equipment that could reduce costs. However, Gansler pointed out that labor costs were high for defense contractors because premium wages had to be paid to attract workers to unstable jobs. Gansler suggested that creative changes in the procurement process were required, and that industrial leaders must provide the new ideas needed.[24]

In a 1977 article Mr. Church, Under Secretary of Defense, noted several efforts to remove investment disincentives from government procurement actions. Efforts to increase investment included:

(1) Lengthening production through the use of multi-year authorizations and contracts.

(2) Reducing or eliminating the specialized nature of military specifications and standards.

(3) Using commercial practices and products, when possible.[25]

A Logistics Management Institute study issued in 1978, titled "A Uniform Profit Policy for Government Acquisition," considered the problem of encouraging corporations to invest in equipment and facilities required for government contracted production. It recognized that government business must compete with civilian business for a limited amount of capital. Profit on government business must be equal to that or comparable commercial business if capital is to be available for government work. Capital has a cost and will be available if that cost is paid. An adequate return on capital employed should be recognized as an essential element of cost. If the cost of capital employed is ignored, capital will not be attracted to government business. Progress payments can be helpful to a contractor.[26]

The Government Accounting Office stated in 1979 that profit policy revisions resulting from "Profit '76" did not achieve the intended result of encouraging investment by defense contractors. The new profit policy was intended to lower production costs by encouraging investment in modern plant and equipment. The GAO said that contractors stated that the new profit policy was not a significant determinant of investment. An analysis of several hypothetical facilities investments indicated that the investments could lead to lower profits for the contractor.[27]

Kaitz pointed out the different approaches that are used by government in industries where it regulates rates. Utilities are allowed to maintain monopolies, but rates are controlled. The DOD attempts to maintain competition in defense procurement. DOD hopes to improve products and prices through competition. However, in the case of defense competition it may discourage investment. Demand for defense products can change significantly from year to year and these changes can be handled better by remaining labor intensive. Higher profits alone are probably not an adequate solution for the problem.[28]

Lenk pointed out the importance of considering profit in relation to the risk involved. The uncertainty of sales and profits create risk. If

this uncertainty is high, the potential profit must be high. Risk in the defense market tends to be related to the time period and the product. In a time of mobilization, risk may be low. Contracts may be terminated at the end of a war. The possibility of sudden termination of a contract creates a very high degree of risk. This risk can be reduced by the inclusion of termination clauses in the contract.[29]

A 1979 GAO report also addressed the question of risk in relation to profitability. Two points made in the report were:

(1) Companies can make capital investments related to commercial business with much greater certainty. Experience in the market allows companies to assign reasonable probabilities to estimates of sales.

(2) Technologies are not adopted for commercial business until they are proved effective. Weapons systems are often put into production with unproven technology. Development continues during production and difficulty often develop. Production is limited until testing is completed.

(3) Low rates of funding limit production.[30]

The GAO also pointed out that multi-year contracting could significantly reduce costs in a number of ways:

(1) Only one contract would have to be negotiated. Multi-year contracting reduced the negotiation costs.

(2) Materials could be purchased in larger quantities, obtaining quantity prices.

(3) Some price escalation could also be avoided if large quantities of materials could be purchased.

(4) Greater efficiency could result from continuous work and a more stable work force.

(5) Longer contracts would attract more competition.

(6) The longer contract would allow more time to amortize equipment and thus encourage investment.[31]

Boileau suggests that an increase in spending in the research and development phases of weapons acquisition could lead to great savings in production costs. The technology could be proven sooner and uncertainties eliminated.[32]

This review of literature on investment incentives indicates that the necessity for investment incentives has been recognized for a long time. The lack of investment seems to have become a particularly serious problem following the Vietnam War. Defense spending has decreased in real terms and personnel costs have absorbed a larger proportion of the defense budget. A number of efforts have been made to determine ways to encourage investments by defense contractors. The following methods of encouraging investment were identified in the literature reviewed:

(1) Profit on defense business should be comparable to commercial business profit.

(2) Contractor investment in facilities and equipment used to complete a contract should be considered in the determination of profit allowed.

(3) DOD should agree to purchase equipment used to increase productivity as defense contracts for the unrecovered cost if the contract is terminated.

(4) Multi-year defense procurement contracts should be awarded.

(5) Fees should be awarded to defense contractors who develop significant means of reducing costs.

(6) Cost savings on defense contracts should be shared with industry.

(7) Industry should be allowed to depreciate plant and equipment more rapidly.

(8) DOD should make realistic long-range procurement plans.

(9) Reduce the number of government employees watching over defense contracts.

(10) Defense procurement should be more stable so that labor force fluctuations could be reduced.

(11) Specialized military specifications should be reduced or eliminated where possible.

(12) Technologies should be developed before going into production.

The process used by business firms to evaluate proposed investments is known as capital budgeting. Effective incentives will have an impact on the capital budgeting process.

Several surveys have been conducted to determine the capital budgeting procedures actually used by business firms. The main purpose of these studies has been to assess the extent of use of the modern discounted cash flow methods for evaluating capital projects. These methods, including the net present value method, the profitability index, and the internal rate return, were designed to replace or supplement earlier methods, such as the payback method and accounting rate of return, that do not consider the time value of money. Previous studies have not been aimed at defense contractors.

In early 1970 Klammer surveyed 369 corporations from a variety of industries. A total of 184 firms returned completed questionnaires for a response rate just under 50%. Of those firms responding to the survey, 57% used a discounted cash flow capital budgeting procedure as the primary means of evaluating proposed investments. Among those not using a discounted cash flow method the accounting rate of return was the primary method for 26%, while 12% based decisions on the payback period. The remaining 5% used urgency. In order to show primary methods for 100% of the corporations that completed the survey form, Klammer assigned those indicating more than one primary means of evaluating capital budgeting proposals to the most sophisticated of the techniques listed as primary.[33]

Fremgen carried out a study of capital budgeting practices in 1971. Questionnaires were distributed to financial executives of 250 corporations in many different industries. Completed questionnaires were returned by 177 or 71% of the executives surveyed.[34] This was the highest return rate among the surveys reviewed. The survey indicated that discounted cash flow techniques were being used by 76% of those firms responding. Some firms used

more than one of the discounted cash flow methods for evaluating capital investments. The internal rate of return was used as the primary capital budgeting decision criteria by 38% of the corporations and net present value or profitability index (a variation of net present value) by 5%. The primary criteria of 22% of the corporations was the accounting rate of return and the payback method was used by 142. Other criteria were reported by 5% of the corporations. The remaining firms did not indicate a primary financial criteria.[35]

Another study of the capital spending planning process was carried out by Petty, Scott, and Bird in the early 1970's. This study differentiated between investments for existing products and those that would be used for new product lines. However, for the purposes of this review the differing product line responses were combined to make them more comparable to the other studies. Questionnaires were sent to the 500 largest U.S. corporations as listed in Fortune. Responses were recieved from 109 or 22%. Again it was found that discounted cash flow methods were predominant, being used as the primary evaluation techniques by 54% of the corporations responding. Once more the internal rate of return was found to be the leading discounted cash flow method, being favored by 39% of the corporations. The accounting rate of return was the primary criteria for 33% of the corporations. Payback period was favored by 12% of the corporations, and 2% used other methods.[36]

Results of a recent study by Schall, Sundem, and Geijsbeek were published in The Journal of Finance in March 1978. The questionnaire was sent to major financial officers of 407 firms identified as being significant in size and/or capital expenditures by the COMPUSTAT tape. Responses were received from 189 financial officers for a response rate of over 45%.[37] The survey indicated increased use of the more sophisticated discounted cash flow methods for evaluating capital proposals. Of the firms responding, 86% used internal rate of return or net present value methods. Larger firms tended to use more sophisticated methods.[38]

The studies reviewed showed a wide variation in response rates which ranged from a low of 22% to a high of 71%. All the surveys indicated that discounted cash flow techniques are being widely used and that their use is

increasing. The internal rate of return has been indicated as the most widely used method of evaluating capital budgeting proposals. None of those surveys were considering investment for defense related production. Our proposed questionnaire will attempt to determine capital budgeting methods currently being used by corporations for commercial business and defense business.

IV. RECOMMENDATIONS

Studies and articles reviewed identified numerous suggested incentives for defense industry investment. This paper has assembled proposed incentives from a variety of sources. For these incentives to be effective they must appeal to defense contractors. The defense contractors will decide whether or not to make significant investment in modern technology for use in fulfilling defense contracts. Presumably this means that the investment incentive must have a significant impact on profit and/or risk. Some of the potential incentives such as giving investment a greater weight in profit determination or giving the contractor a share of cost savings increase profit on a contract. Other incentives such as indemnification and multiyear contracts, have an impact primarily through the reduction of risk. Defense contractors make the decisions to direct more investment toward the defense side of their business. They will invest in manufacturing equipment for defense contracts if adequate incentives are provided. Contractors know what incentives will actually result in additional investment. Therefore, a questionnaire has been developed for defense contractors to obtain their input concerning the impact of suggested investment incentives.

The questionnaire is designed to obtain opinions of defense contractors about current DOD policies and evaluation of current investment incentives. It also contains open ended questions that enable defense contractors to make creative suggestions concerning investment incentives and other means of reducing the cost of weapons systems. The proposed questionnaire has been field tested and the contractors who took part in the test were very enthusiastic and helpful. Some of their suggestions were used to improve the final draft of the questionnaire. This questionnaire, a copy of which may be found in Appendix A, should be sent to major defense contractors to obtain their ideas about incentives that will increase defense industry investment.

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APPENDIX A

DEPARTMENT OF THE AIR FORCE
AIR FORCE BUSINESS RESEARCH MANAGEMENT CENTER (ATC)
WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433

AIR FORCE BUSINESS RESEARCH MANAGEMENT CENTER QUESTIONNAIRE

1. Rank the following capital budgeting techniques in order of importance to your corporate investment process as it applies to defense related investments. (Use a 0 for techniques not used.)*

Accounting return on investment	1	2	3	4	5	6	0
Internal rate of return	1	2	3	4	5	6	0
Net present value	1	2	3	4	5	6	0
Payback period	1	2	3	4	5	6	0
Payback period (discounted)	1	2	3	4	5	6	0
Profitability index	1	2	3	4	5	6	0
Other (describe) ____________	1	2	3	4	5	6	0

____

____

2. Rank the following capital budgeting techniques in order of importance to your corporate investments process as it applies to commercial business investments.*

Accounting return on investment	1	2	3	4	5	6	0
Internal rate of return	1	2	3	4	5	6	0
Net present value	1	2	3	4	5	6	0
Payback period	1	2	3	4	5	6	0
Payback period (discounted)	1	2	3	4	5	6	0
Profitability index	1	2	3	4	5	6	0
Other (describe) ____________	1	2	3	4	5	6	0

____

____

*Definitions of the capital budgeting techniques used in questions 1 and 2 are on the last page of the questionnaire.

FOR THE QUESTIONS 3 THROUGH 22 PLEASE CIRCLE THE NUMBER THAT CORRESPONDS MOST CLOSELY WITH YOUR OPINION.

	STRONGLY AGREE	AGREE	NO OPINION	DISAGREE	STRONGLY DISAGREE
3. The Department of Defense (DOD) should make substantial changes in its profit policies if it wishes to encourage investment in plant and equipment for defense manufacturing.	1	2	3	4	5
4. Most DOD personnel who negotiate defense contracts have a good understanding of the profits required for successful business operations.	1	2	3	4	5
5. Progress payments on defense contracts should be based on costs incurred rather than physical progress.	1	2	3	4	5
6. Regardless of changes in weighted guidelines the government negotiators will allow the same amount of profit on defense contracts.	1	2	3	4	5
7. DOD incentives for defense contractors such as indemnification and sharing cost saving must be increased to lead to a significant increase in investment in manufacturing equipment for defense related business	1	2	3	4	5
8. Interest expense should be an allowable cost on defense contracts.	1	2	3	4	5
9. Increased profits on DOD contracts would lead to investment in manufacturing facilities and lower production cost.	1	2	3	4	5
10. Commercial business yields higher profits than defense business.	1	2	3	4	5
11. The government negotiators will attempt to reduce the cost of contract proposals, regardless of how realistic the proposals are.	1	2	3	4	5
12. Government surveillance reduces the cost of weapons systems.	1	2	3	4	5
13. Our corporation is very anxious to obtain more defense business than it currently has.	1	2	3	4	5
14. Allowance of more rapid depreciation, such as "10-5-3" would encourage greater investment by our corporation in defense-related plant and equipment.	1	2	3	4	5
15. Competition for defense business is greater than that for commercial business.	1	2	3	4	5

FOR THE QUESTIONS 3 THROUGH 22 PLEASE CIRCLE THE NUMBER THAT CORRESPONDS MOST CLOSELY WITH YOUR OPINION.	STRONGLY AGREE	AGREE	NO OPINION	DISAGREE	STRONGLY DISAGREE
16. Firm fixed price contracts lead to lower profits than other types of contracts.	1	2	3	4	5
17. Defense profits should be lower than profits on commercial business.	1	2	3	4	5
18. Increased investment by defense contractors in manufacturing technology could significantly reduce the cost of weapons.	1	2	3	4	5
19. Defense business is riskier than commercial business.	1	2	3	4	5
20. The small quantities of weapons and material currently purchased does not justify increased investment in manufacturing equipment.	1	2	3	4	5
21. Our corporation would make significant additional investments in manufacturing equipment for defense if the government would agree to purchase the equipment at the conclusion of the contract for the amount of the investment not recovered.	1	2	3	4	5
22. Our ability to accept significantly more defense business is limited because of a shortage of necessary parts or raw material.	1	2	3	4	5

23. Rank the following qualitative factors that would influence investment decisions in your firm:

Employee morale ________

Employee safety ________

Environmental factors ________

Legal ________

Maintaining labor force ________

Management goals ________

Prestige ________

Other (Explain) ____________________ ________

____

____

24. In evaluating capital budgeting proposals the minimum acceptable rate of return for our corporation is:

Cost of a specific source of funds	______
Firm's historic rate of return	______
Industry historical rate of return	______
Target rate	______
Weighted cost of sources of funds	______

25. The rate of return currently being used to evaluate defense related capital projects in our corporation is:

______ %

26. The rate of return required for commercial business related projects is:

higher ______
lower ______ than that required for defense related investments
the same ______

27. The Department of Defense is very interested in encouraging corporations to invest in modern technology for defense contracts. What are the most effective actions that DOD and/or Congress could take to encourage your corporation to investment in defense related production equipment?

28. Regardless of prior questions, what are the most essential steps that DOD and/or Congress should take to reduce the cost of weapons and materiel?

CAPITAL BUDGETING TECHNIQUES DEFINITIONS

1. Accounting return on investment: The ratio of average annual profits after taxes to the average investment on the original investment. It is based on accounting income rather than cash flows, and does not consider the time value of money.

2. Internal rate of return: The discount rate that equates the present value of cash inflows from an investment to the cost of the investment.

3. Net present value: The present value of future cash inflows minus the present value of the cost of an investment.

4. Payback period: The time required to recover the cost of the investment.

5. Payback period (discounted): The time required to recover the cost of an investment if the cash flow is discounted.

6. Profitability index: The ratio of present value of future returns to present value of cost of the investment.

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FINAL REPORT

IMPROVING INFORMATION MANAGEMENTS SKILLS OF THE AIR FORCE BUSINESS RESEARCH MANAGEMENT CENTER PERSONNEL TO ACHIEVE OPTIMUM EXTENSION AND PRODUCTIVITY OF RESEARCH SERVICES

Prepared by:	Sallye S. Benoit, Ph.D.
Academic Rank:	Associate Professor
Department and University:	Administrative Services Nicholls State University
Research Location:	Air Force Business Research Management Cneter (AFBRMC/RDCB) Wright-Patterson AFB, OH 45433
USAF Research Colleague:	Colonel Martin D. Martin

Date:	September 1980
Contract Number:	F49620-79-C-0038

IMPROVING INFORMATION MANAGEMENT SKILLS OF AIR FORCE BUSINESS RESEARCH MANAGEMENT (AFBRMC) PERSONNEL TO ACHIEVE OPTIMUM EXTENSION AND PRODUCTIVITY OF RESEARCH SERVICES

by

Sallye S. Benoit

ABSTRACT

An overview of management's problems with white-collar productivity is given. Improved communication (internal and external) and information management are suggested as two paths which can lead to extended services and increased productivity in an office environment. A sample study of the communication and the information management operations in the Air Force Business Research Management Center is described. The literature is reviewed, and the technique of observation and personal interview, to analyze and evaluate office problems, is detailed. Recommendations for optimum use of personnel and equipment are given, and suggestions are made for further studies to be conducted.

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Captain William L. Glover, who was accidentally killed during June 1980, is remembered for his exceptional way with people and for his particular interest in the Summer Faculty Program. Also the support and encouragement of Colonel Martin D. Martin, Executive Director, AFBRMC/RDCB, is deeply appreciated.

I. INTRODUCTION:

During the 20-year period following World War II, American productivity increased 3.2 percent per year; and with this increase came a steadily improved standard of living for most Americans. However, in the late 1960's the rate of production began to drop; the "good old" American way of life was beginning to feel the impact. In 1979, a -0.5 percent decrease was recorded.[1]

What has caused productivity to decline? Historically the major portion of the U.S. work force has been blue-collar, but a change from a blue-collar to a white-collar work force has occurred. Studies indicate that by the middle of the "80's" white-collar workers will comprise approximately half of all employment in the nation. While improving productivity has always been an important objective of management at the manufacturing level, white-collar productivity has often been ignored. But in today's problem-riddled office environment, management has a mandate to search for ways to increase office production.

Inflation has also contributed to declining productivity in the office. Office costs have doubled during the past ten years, and the indication is that for the next several years an increase of 12-15 percent per year is anticipated. Skyrocketing energy costs, environmental regulations, decline in research and development, and tax and depreciation policies have also taken their toll.[2]

Managements on all levels are attempting to cope with this multifaceted problem. The need to carry out effective programs aimed at increasing white-collar productivity has only recently been recognized. However, for any program to be successful, it must occupy a top position in the organization's objectives. As an added impetus, the research arm of industry and the scientific community needs to work with management to find the "keys" to expand the production of the white-collar worker.

The Air Force Business Research Management Center (AFBRMC) recognizing that the decline in productivity in the U.S. was detrimental to the health of the country's economics and understanding its unique position in the research community of the Air Force, agreed to an evaluation of its own productivity.

In 1973 the Air Force Business Research Management Center was established to function as the Air Force focal point for a contracting

and acquisition research program. The Air Force hierarchy determined that an agency such as the AFBRMC was needed to improve the manner in which the Air Force conducted its business research management practices. This research could shorten the acquisition process, reduce acquisition and ownership costs, improve acquisition efficiency, and improve the utilization of acquisition and contracting professionals.[3]

According to AFR 20-5: "The Center will be organized to develop a research program designed to match a need with an existing research capability--either in-house (in the Air Force or the Defense Department) or through an outside organization (academic business, or professional association) and shall be responsible for managing or monitoring performance of each research project to completion."[4]

AFBRMC identified four primary objectives to help accomplish the mission as established in its charter. These objectives are need identification, project management, results management, and consulting. In the spring, 1979, an off-site work session was held by the Center to identify objectives that would improve Air Force acquisition research in the 1980's. In the self-evaluation process, the four primary objectives were reaffirmed and two more objectives were added: organizational maintenance/development and the enhancement of the AFBRMC public image.

Because of the role that the AFBRMC occupies in the acquisition research community, the volume of work that is produced in the Center, and the increased concern over the decline in productivity (especially in the white collar area), a study of this organization's personnel information management, and communications was conducted.

Procedures of the Study

A search through the literature was made at the beginning of this study. Information was then gathered through the primary research methods of observation, personal interviews, and examination of office documents.

The observations were made in the office over a ten-week period. Dawe and Lord defined observation as a primary research activity that is conducted by carefully watching the activity surrounding the object of investigation according to a thoughtfully preplanned criteria.[5] "One of the

ways to overcome the major disadvantages of asking people for descriptions of themselves is to obtain the data by watching and recording what happens in the situation under examination."[6] Weiss stated that random observation of personnel is a technique whereby administrators can effectively determine how much time is acutally spent in work.[7] Using these criteria, objective observations were recorded in a systematic manner.

Personal interviews were also conducted during the ten-week study. "The techniques of interrogation can be the preliminary step in many research problems, but it could constitute the whole of the research work."[8] Helmstadter said that one major advantage of the interview approach was the directness involved. If the researcher can assume that the respondent has no reason to distort his/her answers, then asking persons to describe their attitudes and perceptions is the most simple and direct approach to use. However, he cited two disadvantages: interviewer characteristics might influence responses and an assumption is made that the respondent is not only willing but able to provide reliable results.[9] Members of the military staff and civil service personnel at AFBRMC were interviewed and the respondents gave evidence of being willing and able to provide reliable answers to the queries.

The final type of primary research used to complete the study was a search through the office documents. Included in the investigation were daily correspondence, reports, forms, logging records, brochures, catalogs, contracts, and budgets. Records contain vital information and many times this information can only be obtained by a search through company files.[10] All office records were made available to the researcher.

A Selected Review of Related Literature

An investigation of selected research relative to the study of productivity in the Air Force Business Research Management Center was reviewed under three broad categories:

(1) Productivity and management
(2) Information management--word processing,
(3) Internal and external communication.

Productivity and Management

The decline of productivity in the United States is a growing concern. The Nation's business and political leaders will have to reverse the process

or the country will have to suffer unpleasant consequences. Perhaps the most important area of human activity is managing. A task basic to managers at all levels and in all types of business organizations is the maintenance of an environment in which individuals or groups can work together to accomplish preselected missions and objectives.[11] In the second decade of the 20th century, Frederick W. Taylor, the father of scientific management, set forth the following fundamental principles:

(1) Replace the rules of thumb with sciences (organized knowledge),
(2) Obtain harmony in group action rather than discord,
(3) Achieve cooperation of human beings rather than chaotic individualism,
(4) Work for maximum output, rather than restricted output,
(5) Develop all workers to the fullest extent possible for their own and their company's highest prosperity.[12]

Over seventy years later, leaders of business and industry still attempt to incorporate these principles into their management goals.

One of the Taylor's first studies using the "scientific" approach was applied to the loading of pig iron. By observing current performance, he found that maximum performance would allow for the loading of approximately four times as much tonnage as was being done currently. He implemented his research by using the most efficient gang and having them load in the most efficient manner; performance was increased fourfold while employees' earnings were increased 50 percent through incentive pay.[13]

In the late 1920's and early 1930's, Elton Mayo, a Harvard professor, and his associates conducted a series of experiments (Hawthorne Studies). These studies, conducted at the Western Electric Company, recognized that motivation is a part of a complex system of human behavior. The researchers were unable to prove a direct relationship between environmental factors and output, but they discovered something unexpected--people are concerned with what other workers think of them and that because of this the "boss" should take an interest in what workers do on the job. This means that managers who do not have the enthusiastic support of the groups they supervise will be unable to motivate individual members to a significant degree.[14]

Another researcher who was cognizant of employees and their needs was Abraham Maslow. During the summer of 1962, he studied the Non-Linear Systems, Inc. plant and from this study he developed the following propositions:

(1) The best managers are psychologically more healthy than the poorer managers,

(2) The best managers increase the health of the employees they manage through fulfilling the basic needs for job satisfaction, recognition, purpose, usefulness, justice, law and order, etc.

(3) The healthier workers profit the most from eupsychian management.

(4) The better man and the better group are the causes and effects of each other.

(5) There is a network of interrelations. The better the society, the better the productivity; the better the managers, the more psychologically healthy the individual man; the better the individual man, the better the enterprise.[15]

Maslow concluded that employees will work better for good management rather than for poor management. Good management fosters the growth of good employees and produces a process whereby growth gains momentum and expands limitlessly.

Work measurement of machine and other factory operatives was one of the cornerstones of modern management techniques. Although work measurement failed to achieve substantial improvements in factory productivity, the increased concern over white-collar productivity caused management to use work measurement for clerical employees; and this technique is being pursued more vigorously now than at any time in history.[16]

Little contends that the act of measurement is generally nonproductive, because every moment spent counting, calculating, and analyzing is time spent away from producing.[17]

Motivation of the employee is one of the fundamental principles in the process of directing and leading. Management can no longer satisfy workers by financial reward alone. Motivation is a highly complex subject, which depends upon the individual's personality, perception, and expectation. If an environment is to be designed in which people will perform willingly, management must respond to the motivation of the individual.[18]

Time management is another facet of management that needs to be studied in the search for improvement in productivity. Time is a resource that sometimes is taken for granted or perhaps is never considered as a resource. Time, like sleep, cannot be accumulated or made up. Once lost, this valuable commodity is gone forever. It is a resource that slips by whether a choice is made or not. Chaplin Tyler stated, "Time is the most inexorable

and inelastic element in our existence."[19] In order to produce at optimum efficiency, both personnel time and equipment time must be utilized to the fullest extent.

Carlson, Drucker, and MacKenzie advocate that executives keep a time log. Carlson stated that it was one thing for an executive to feel he does not have time to work alone or to discuss questions of development with his subordinates, and another to know how much time he spent alone in his office or how many times development questions were actually discussed.[20] Drucker contends that rather than planning first how one wishes to spend his time; one first should discover where his time is going.[21] MacKenzie comments that trusting one's memory is risky business, and could even create unnecessary crises.[22]

Managements of yesteryear and today share many of the same problems but a highly educated work force, a more technologically complex society, and an ever-changing world have created new areas of challenge for today's executive.[23] In referring to one of Taylor's fundamental principles of management, Hellweg points out that interdependent personnel relationships are an important fact in any organization. If this relationship is healthy, then productivity, efficiency, and attainment of organizational goals are possible.[24]

Management has been coping with the problems and questions dealing with productivity for many years. Research studies have formulated principles and offered solutions to industry, government, and business leaders. Much of this information was devised from and for the blue-collar work force; now management must adapt the old ways and seek new ones in order to find satisfactory solutions for the problem of white-collar productivity.

Information Management

Paperwork is one of the most serious problems facing American business and government today. Information and paperwork go hand in hand, and they occupy a vital role in busines ecology. Just as other pollutants contaminate the air, sea, and soil, paper pollutes and plagues the offices and boardrooms of business. Management's failure to create, control, and communicate information is causing lost profits and increased expenses.[25]

The 1970's was the decade in which the discussion was "The Office of the Future." The 80's are here and it is time to turn the discussion to action. The technology that is available today is not an entity in itself, nor is it a substitute for people; instead it is a means for augmenting human potential.[26] This technology is a multi-disciplined challenge which allows information to be sent to the right person, in the right form, at the right time.[27]

Information is a valuable resource that has long been regarded as a free and unlimited commodity, but now less energy must be used to produce more information. Management of information is an idea whose time is long overdue. Data processing and word processing are the systems that will help bring this idea to fruition. Word processing is a qualitative process; data processing is quantitative. Because word processing was the focus of this study, attention was directed to that area.

Word processing, the phrase originally coined by the International Business Machines Corporation, is one of the most readily available solutions to the problem of decrease in productivity. Word processing procedures can be flexible if management will develop methods that change according to the various levels of task difficulties.[28] If word processing is to be effective, a word processing staff must interact with management, and thus relieve managers of routine tasks so that more productive activities can be undertaken. In establishing a word processing operation, management should remember that the operation is only as effective as the skills of the personnel who work in this electronic environment.[29]

Word processing first made its way into large offices with the use of a magnetic media typing station. Since that time, equipment has become more sophisticated and the cost of acquiring word processing capabilities has declined. With the decrease in cost and the increase in usefulness of the equipment, small offices have begun to adopt it according to their needs.[30] As with most innovations, growing pains develop; to cope with these pains, firm guidance is needed. Identification of problem areas is the first step in setting up guidelines for a system, and Tilton of Systems Design, Format Systems, Inc. has cited five principle causes of growing pains:

(1) Individualism in operators,

(2) Coordination of machine models,

(3) Originator-operator ratio,

(4) Personnel turnover,

(5) Expansion of boilerplate.[31]

In order for word processing to be effective, the problems must be recognized and studied. Management should tailor equipment to its own needs and find adequate solutions to the problems.

Why should management consider the establishment of word processing facilities? Effectiveness has been proved in the following areas: Word processing cuts costs by increasing productivity, opening up more distribution channels for information, generating documents of better quality than those produced by other means, and allowing the user to do things not possible with other equipment.[32]

The Office of Records and Information Management (ORIM) has spent four man-years on a research project. This project is the first tentative step toward understanding the nature, costs, and efficiencies of the typewriter and the word processing systems. The study uncovered a major shortcoming in federal word processing. The operators of the systems have not been completely trained on all of the features of the system. Many of the systems are not being used to their maximum effectiveness. From the study, ORIM will develop a set of objectives and guides, and from these guides meaningful goals that can be achieved should be established.[33]

The evolution of the automated office has begun. Changes in the office environment will continue for years to come. The changes will not happen overnight. As the evolution takes place, jobs, procedures, and management techniques will also change. Wise management will try to anticipate the changes and channel them for the optimum benefit of their organization.

Communication

Problems in communication are so commonplace that the difficulty is probably not with people as much as with the processes they use. The ability to communicate has been taken for granted, but what is assumed to be a simple, natural process is very complex.

Most managers have a common objective in communicating. They are attempting to influence the way things happen through what they say and do. Managers also recognize that communication barriers exist--between managers and workers, between professional and technical staff. People misunderstand

and mistrust others for various reasons: differences in backgrounds, responsibilities, goals, values, experience, education. Some barriers are inbuilt and not much can be done about them. Management and individuals can do something about others.[34]

Dawes and Lord stated that one of the best ways to improve the information system of an organization was for each individual in the company to master the basic techniques of problem solving and organization, the fundamental principles of written presentation, and the function of effective communication.[35]

Martin stated that critical to the success of the project manager is communication that provides a mechanism for informing personnel as to the organization's mission and objectives, and explaining personnel's roles in implementation of stated objectives. Effective communication helps create an environment where individuals are aware of events and where they can personally relate to problem solving and other management efforts.[36]

Janis explained how communication is used internally and externally by an organization. It is used inside the organization to inform management, to coordinate organization activities, to instruct workers, and to maintain and improve morale. Externally it is used to move goods and services; to communicate with stockholders, government, and the public; and to create a favorable climate in which business can be conducted.[37]

DeMare relates the information explosion to communication. "Lack of care in selection of the information to be transmitted and in rationalization of the various channels, media, and forms leads either to chaos from an overflow of communication, the wrong kind of communications, or to an 'information hunger' which may eventually lead to the organization's collapse . . . Quality is becoming more important than ever before from an economic viewpoint in our highly complex and developing world."[38]

Barry Maude reinforced DeMare by stating that information is the raw material of sound management. It is the tool from which decisions and policies are formed. Information failure can kill an organization. However, in some modern businesses, the proliferation of information can cause overkill. Superflous information can choke the channels of communication.[39]

Successful communication is vital to the functioning of any organization. It cannot be considered as a separate part of the activities of the business, for it permeates every facet. Communication is a continuous activity. To be effective, management must realize that in addition to human processes, the mechanical tools of communication must be efficiently managed.[40]

Communication encompasses a wide array of activities--some are effective, others are not.[41] One questionable method that is frequently employed in military and government communications is the use of acronyms and abbreviated terms. These "handy" communication shortcuts have been used for centuries, but Ralph DeSola commented:

> "Abbreviations of every sort cover contemporary civilization like a deep and ever-deepening snowdrift, concealing the main features of the landscape: leaving the beholder mystified and perplexed by the overwhelming obscurity imposed by these letter and number combinations."[42]

Communication can be realistically viewed as fundamental to all managerial activities and as the core process of organizational behavior.[43] It can make or break an organization.

II. OBJECTIVES:

The primary objective of this project was to investigate the productivity of the white-collar employees in the Air Force Business Research Management Center (AFBRMC). Three areas of activity were explored. The researcher:

(1) Assessed the quality and quantity of work produced by the military and civil service staff of the AFBRMC.

(2) Investigated the management of information--word processing--in relation to input, throughput, and output.
Input - idea stage. Someone needs to communicate.
Throughput - process stage. People, procedures, and equipment needed to develop the communication.
Output - completed stage. Document is in finished form.

(3) Evaluated the effectiveness of internal and external communication.

III. APPROACH:

Problem: Is the optimum in productivity being attained by the personnel of the Air Force Business Research Management Center (AFBRMC)? The study investigated management and productivity, information management, and communication.

Management and Productivity

The AFBRMC is assigned to HQ USAF, and receives functional guidance from the Director of Procurement Policy, Brig Gen Joseph H. Connolly. The organization chart depicts AFBRMC's position in the organization (see Figure 1). The Executive Director is responsible for developing the procurement research program under the guidance of the Board of Advisors. The Board is chaired by the Director of Procurement Policy, HQ USAF; members of the Board include representatives from HQ AFSC/PM, HQ AFSC/DS, HQ AFLC/LO, HQ AFLC/JA, HQ AFLC/PM, HQ AFCC/EPK, HQ MAC/LGC, and HQ ATC/LGC.

The Board meets semiannually and provides guidance and obtains support for the overall research program. The purpose of the winter board meeting is for the Board to identify the needs of the Air Force community. The identified needs are then compiled and published by the AFBRMC in a catalog which is mailed to the military and academic communities. At the summer meeting, the AFBRMC gives a progress report and outlines plans for the coming year.

The staff of the AFBRMC is military and civil service in composition. The military positions are Executive Director, Colonel designation; five Research Managers, designated as a Lt Col (Deputy Director), two Majors, and two Captains. Twelve active Reservists complete the military make-up. The civil service personnel include a GS-6, GS-4, two student workers, and a Copper Cap trainee.

The Executive Director shall have the qualifactions for, and be granted the academic status of, Adjunct Professor, AFIT. He will be responsible for the day-to-day management of the Center. His duties and responsibilies as outlined in AF 1378, 10 June 1976, are as follows:

ORGANIZATIONAL CHART

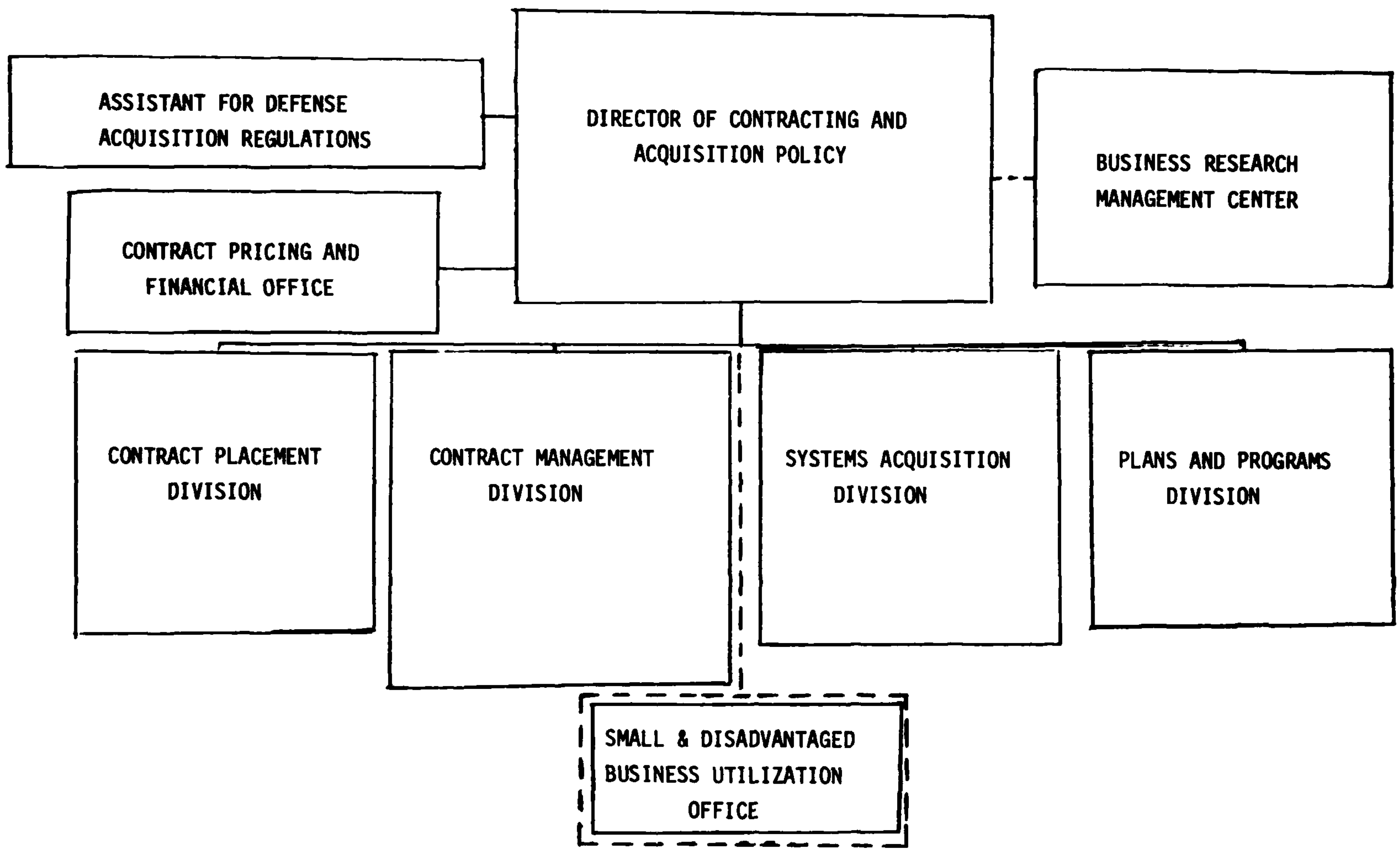

FIGURE I

DUTIES AND RESPONSIBILITIES: Directs the center in its mission as the focal point to coordinate, sponsor, and evaluate research in business-oriented procurement methods. Assigns topics to the center research project managers, monitors the progress of research, and provides guidance and expert advice as required on both functional and academic questions. Reviews research products and proposed implementation actions. Serves as the prime interface between the center and the Air Staff, operating commands, the academic community, and industry. Performs other duties as may be delegated by the Director of Procurement Policy, Headquarters USAF.

Five Research Managers are assigned to the AFBRMC and one of the managers is designated as the Deputy Director. Listed below, as stated in AF 1378, 10 June 1976, are the Deputy Director's and the Manager's duties and responsibilities.

6516, Lt Col, Deputy Director, DUTIES AND RESPONSIBILITIES: Responsible for the general operation of the office under the direction of the Executive Director. Involved in personnel planning, financial planning, and research area management. Identifies procurement practices that require research in order to develop improved methods. Establishes and assigns research projects under direction of the Executive Director to industry, the academic community, and internal DOD agencies. Continuously monitors and reports on the status of the research. Reviews and tests research products for practicality of implementation. Develops and prepares instructions and procedures for implementation of new concepts. Serves as the focal point for dissemination of research findings and information. Serves as consultant on the implementation of research recommendations. Establishes and maintains liaison with industry, the academic community, and DOD agencies. Performs other duties as may be delegated by the Executive Director.

Research Managers - DUTIES AND RESPONSIBILITIES: Identifies procurement processes that require research in order to develop improved methods. Establishes and assigns research projects, under the direction of the Executive Director, to industry, the academic community, or internal DOD research agencies. Continuously monitors and reports

on the status of research. Reviews and tests research products for practicality of implementation. Develops and prepares instructions and procedures for implementation of new concepts. Serves as the focal point for the dissemination of research information and findings. Serves as consultant on the implementation of research recommendations. Establishes and maintains liaison with industry, the academic community, and DOD research agencies. Performs other duties as may be delegated by the Executive Director.

Under the heading of other duties, the Managers perform many administrative functions. These functions are assigned as the need arises. Equipment officer, voting officer, campaign officer, space officer, and budget officer are a few of the administrative type tasks which the Managers must find time to execute.

The reservists that are assigned to the AFBRMC read and summarize research projects for the Topics Catalog, engage in research, evaluate research reports, and perform other duties as the need arises. These men are on active duty for two weeks a year, plus eight hours a month.

The GS-6 is the top civil service employee in the AFBRMC. She serves as assistant to the Director of the Center and in that capacity receives his visitors and telephone calls, routes the incoming mail, takes dictation, coordinates his calendar, and assists with all activities in which the Center is involved. The GS-6 directs the workflow in the office and supervises the student workers. She aids the Research Managers on request. She is also responsible for maintaining a library of procurement, acquisition, and acquisition research projects.

The GS-4, presently filled by two half-time employees, takes dictation from the Director and other office personnel, operates the CPT-8000, and assists the GS-6 with other office duties.

Two student workers type, answer the telephone, and perform other office duties as delegated by the GS-6.

The AFBRMC is involved in a trial training program in which civil servants, Copper Caps (CC), are trained in the Center for a period of approximately three months. The Center has agreed to train three selectees. These trainees are part of a program designed to acquaint them with the acquisition and procurement procedures of the Air Force Civil Service. The Copper Caps are assigned to various offices at their home base; the program is designed for a three to five year period. While a member of the staff, the CC is directed by the immediate supervisor of the unit.

The workload in the office is extremely heavy, and the activities can be divided into two categories, projects and routine.

The projects are the semiannual board meetings, the Acquisition Research Topics Catalog, the Annual Business Research Report, the annual Acquisition Research Symposium, and the budget.

The routine procedures include working with researchers (proposal or contract stage), conducting/attending staff meetings, originating and answering daily correspondence, logging/tracking information and projects, managing incoming and outgoing telephone calls, assisting in a summer faculty program, visiting universities, providing support for reservists, and handling miscellaneous occurrences.

Projects

Many administrative duties in addition to the clerical work must be performed in preparing for the Board meetings. The members are contacted and arrangements for their transportation and/or housing are made. Facilities to house the meeting must be reserved--coffee and lunch provided. The presentation of the meeting must be well organized, with an agenda that can move smoothly but that can also have flexiblility. Reports on projects must be prepared, handouts typed and printed, and transparencies made.

The Executive Director plans the meeting with input from the Research Managers and the GS-6. The Research Managers are responsible for reporting on their projects. They prepare information for the handouts and the GS-6 compiles the information. The GS-4 assists in the compilation.

The "Acquisition Research Topics Catalog" gives highlights on specific research needs and objective statements. The purpose of the catalog is to increase the availability of Air Force acquisition research problems to researchers and to improve the quality of the proposals received. The topics are divided into five major areas: Requirements Management, Business Relationship, Program Management, Acquisition Logistics, and Business Environment. The research need and the objectives are given for each topic; the 1979 Catalog lists over eighty topics.

The Research Managers are responsible for writing the research needs and the objective statements for the catalog; active reservists may be asked to help. The GS-4 types and proofreads, and the GS-6 edits and "proofs" the final draft.

The "Annual Business Research Report" provides summarized information on the latest research in areas that are of concern to the acquisition community. The first part of the report provides the research program status. Information included in this section are title of the program, a summary of the study, and the significance of the findings. Part II is a bibliography of completed studies. If detailed information on a subject that has been summarized in the report is needed, final reports are available.

Summarizing the projects for the Annual Report is the task of the Research Managers, and reservists may be asked to assist. The civil service personnel perform the same tasks as they do for the Topics Catalog.

The annual Acquisition Research Symposium is sponsored every fourth year by the AFBRMC. Over 400 members of the acquisition community attend. Sponsorship involves calling for papers, reviewing the papers, editing and printing the Proceedings, and providing all administrative arrangements (site selection, distribution of registration packets, collection of money). AFBRMCs responsibilities during the three off years include delivering papers, identifying section managers and participating on panels.

The primary responsibility for the symposium rests with the Executive Director with many duties delegated to the Research Managers and the GS-6. The entire office staff is involved in preparing for these conferences.

The budget is prepared for two years in advance. Much planning and thought is given to this operation. Every year a two-year projection is required and a status report is submitted every quarter. These reports are most important as the monies that are dedicated for the next year will depend upon the financial condition of the organization this year. (If the funds are not spent in the current year, appropriations will be cut for the following year).

The preparation of the budget is the duty of a research officer who is designated as the budget officer and the GS-6.

Routine

The routine work of the Center is demanding and time consuming, and it is produced around the five major projects. The title routine does not imply unimportant, but denotes essential work that must be executed on a day-to-day basis.

The work procedure for an unsolicited proposal is detailed in a flow process chart on the following page (Figure II). A great deal of work for the research associates and the secretaries is involved, and it is possible for the proposal to get delayed at various points in the process. The flow process chart was devised to identify the delays and to help eliminate a bottleneck in the work flow of the office. The chart was jointly constructed by the GS-6, a research manager, and the researcher.

If the AFBRMC does not have the funds available to finance a project, the staff will try to locate funds. If the project requires a substantial appropriation, then the staff refers the researcher to another source.

When a proposal reaches the contract state, a purchase requisition (PR) procedure is instituted. The process commences with the writing of the statement of work (SOW); an example is presented on the following pages (Figure III). The SOW is followed by the Award Contract, Transmittal of Contract Number, and the Material Inspection and Receiving Report. The research manager is responsible for writing the SOW and signs the contract as the Air Force's representative. After the contract is signed, the research manager works with and provides help, as needed, to the researcher. The help might consist of locating information, conducting conferences, reviewing progress reports, obtaining research support, providing bibliography searches, and offering encouragement. When the final document is received, the Material Inspection Report is submitted. A briefing is held for the researcher to present his/her finds to the originator of the need, other interested parties, and the staff of the AFBRMC.

Staff meetings are usually held once a week. In an informal atmosphere, each individual is asked by the Director to comment on his/her activities of the preceding week and plans and/or ideas for the next week. The Director leads the meetings, and the researcher was impressed with the three meetings that she attended. The meeting can be very productive, especially if each person is prepared. If the staff is unprepared, the activity loses its effectiveness as a communication channel and as a measure of accountability. The staff meetings are very important to the Center as they provided an avenue for the staff to have direct input into the organization.

	PROPOSAL FLOW PROCESS CHART	Operations	Transportation	Inspection	Delay	Storage
1.	Need origination (Board/major commands, etc.)					
2.	Write-up of identified needs for Topics Catalog (Research Manager)					
3.	Topics Catalog compiled (Project Officer)					
4.	Topics Catalog edited (Project Officer/Administrative Assistant)					
5.	Topics Catalog typed (Secretary)					
6.	Topics Catalog proofed (Administrative Assistant)					
7.	Topics Catalog printed (Printing Office - 3-4 weeks)					
8.	Topics Catalog mailing preparations begin (Student Aides)					
9.	Topics Catalog mailed (Student Aides)					
10.	Catalog received/reviewed/project(s) selected (Researchers)					
11.	Initiated contact made with BRMC Research Manager (Researcher/Research Mgr)					
12.	Proposal prepared and mailed to BRMC (Researchers)					
13.	Proposal received and routed (Secretary)					
14.	Proposal logged and suspense date established (Administrative Assistant)					
15.	Form acknowledgement letter prepared (Secretary)					
16.	Proposal package (Acknowledgement ltr/proposal/suspense ticket) routed to research manager (Secretary)					
17.	Signs acknowledgement letter and initially reviews proposal (Research Mgr)					
17A	Route proposal for evaluation, consultation, or rejection (Research Mgr)					
18.	Returns proposal to secretary (Research Manager)					
19.	Pulls proposal 15 days prior to established suspense date and gives it to the research manager (Administrative Assistant)					
20.	Begins evaluation of proposal (Research Manager - 15 day time frame)					
21.	Remind research manager two days prior to suspense date that evaluation is due (Administrative Assistant)					
22.	Concludes evaluation (Research Manager)					
23.	Determine proposal action and prepare letter to researcher (Research Mgr) ACTION a. Suggest changes to initial proposal b. Rejected c. Accepted/Funds Available d. Accepted/Pending location of alternative funds e. Accepted/Future funding in next FY					
24.	Letter typed and new suspense dates established (Secretary/Adm Assistant) a. Changes - 15 days after receipt of changes b. Rejected - no action c. Accepted/Funds Available - 30 days for completion of PR package d. Accepted/Alternative Funds - 30 days to locate possible funds e. Accepted/Future Funding - Adm Assistant indicates action on proposal log					
25.	Letter routed to research manager for signature (Secretary)					
26.	Letter mailed to researcher.					

FIGURE II

STATEMENT OF WORK

AN EVALUATION OF THE EFFECTIVENESS OF THE INCENTIVE TYPE CONTRACTS IN THE AEROSPACE INDUSTRY

1.0 INTRODUCTION (OBJECTIVE)

1.1 The objective of this study is to thoroughly evaluate the effectiveness of the incentive type contracts in the aerospace industry, including cost plus incentive fee (CPIF), fixed price plus incentive fee (FPI and FPIS), award fee and overhead incentive contractual clauses. Many existing DOD contracts have an incentive fee clause, yet the effectiveness of these clauses has been brought into question. This study will answer many controversial issues about incentive contracting by analyzing their basic assumptions.

2.0 SCOPE

This project will have four phases as detailed in paragraph 4.0. The efforts will include examining the existing body of literature pertaining to incentive contracting, conducting interviews with government and contractor acquisition managers, constructing questionnaires to be completed by acquisition personnel, analyzing all data to test research hypotheses, and documenting the study and its results by writing reports and giving briefings. These tasks will be aimed at thoroughly evaluating the effectiveness of incentive type contracts in the aerospace industry.

3.0 BACKGROUND

Contracts with incentive clauses are designed to decrease costs, increase performance of the end-product, or encourage the completion of some other government goal. Many DOD prime contracts have used incentive clauses. However, the effectiveness of such contracts has been brought into question by numerous studies. Most of the previous studies have been done in a piecemeal fashion. This study will be comprehensive. The results should provide a basis for the appropriate use of incentive type contracts.

4.0 STUDY REQUIREMENTS/TASKS

Contractor responsibilities are included under the following phases.

4.1 Phase I

4.1.1 Research the existing body of literature on incentive contracting and develop an annotated bibliography.

4.1.2 Develop a plan for, and subsequently conduct, interviews with key industry and government officials. These interviews, and all the remaining study tasks, will be aimed at evaluating the use and effectiveness of incentive contrac by analyzing the basic assumptions about them. The motivational, contractual, and administrative aspects to be addressed are listed below.

FIGURE III

4.1.2.1 Motivational Aspects

4.1.2.1.1 Does an incentive contract influence the level of achievement of the contractor?

4.1.2.1.2 How effective are negative incentive clauses in motivating performance?

4.1.2.1.3 How important is it to have incentives keyed to individuals? Also, who should the arrangements be communicated to?

4.1.2.2 Contractual Aspects

4.1.2.2.1 Do the final costs of most incentive contracts end up near their targets?

4.1.2.2.2 Are the targets of the incentive contract higher than the targets of alternative types of contracts?

4.1.2.2.3 What are the most significant variables in determining which type of contract is needed?

4.1.2.2.4 Are the contractual agreements designed for intentional overruns?

4.1.2.2.5 Are the rules of thumb used for the structuring of incentive contracts valid?

4.1.2.2.6 Is the complexity of the incentive structure a significant factor in determining the administration and subsequent effectiveness of the incentive contract?

4.1.2.3 Administrative Aspects

4.1.3.2.1 Does the Government eliminate the opportunity for incentives to work by its administration of the contracts?

4.1.3.2.2 Does the cost of administering the incentives generally outweigh the savings of the incentive type contract?

4.1.3 Submit a report describing Phase I accomplishments to include an annotated bibliography.

4.2 Phase II

4.2.1 Develop and distribute a questionnaire to be sent to industry and government personnel. The questionnaire will address the aspects listed in paragraphs 4.1.2.1 through 4.2.1.3.

4.2.2 Conduct a series of small conferences with a selected sample of industry and government personnel.

FIGURE III (continue)

4.2.3 Complete a pilot case analysis.

4.2.4 Submit a report describing Phase II accomplishments, which includes the selection of sample companies, the methodology used in forming the sample, a precise statement of the hypotheses to be studied, a pilot case report, and a plan for Phase III.

4.3 Phase III

4.3.1 Complete a case analysis of a small selected set of contracts and aerospace companies.

4.3.2 Complete the analysis of the questionnaire that was previously sent to industry and government officials and compare to the results of the case study listed in 4.3.1.

4.3.3 Submit a final report which integrates all interviews, small group meetings, questionnaires, and case studies. This report shall contain, as a minimum, the background of the study, the existing literature on incentive contracting, study methodology, assumptions, limitations, analysis of data and hypotheses, case studies describing the effect of incentive contracts on organizational behavior, conclusions, and recommendations for further studies.

4.3.4 Present three briefings on the study results and recommendations.

5.0 DELIVERABLE ITEMS

5.1 Technical Report (Phase I)

The Phase I technical report will be submitted to the AFBRMC five months after contract award and meet the requirements of 4.1.3.

5.2 Technical Report (Phase II)

The Phase II technical report will be submitted to the AFBRMC fourteen months after contract award and meet the requirements of 4.2.4.

5.3 Technical Report (Phase III/Final)

5.3.1 The final technical report will be submitted to the AFBRMC eighteen months after contract award. This report will consist of the formal documentation of the study and a two-page summary and meet the requirements of 4.3.3.

5.3.2 Two-page summary. This summary will describe the highlights of the study and list major findings and conclusions. The summary will also list management considerations on the appropriate use of incentive type contracts.

FIGURE III (continue)

5.4 Briefings of the Study Results

The contractor shall present briefings of study results after the final report is submitted to the AFBRMC.

5.4.1 Informal briefing to the AFBRMC. The informal briefing will be given to the AFBRMC at Wright-Patterson AFB within two weeks after submittal of the final report. At this time, the contractor shall also answer questions and concerns about the study and its results.

5.4.2 Formal Briefings. The two formal briefings will be given to key Air Force officials in the Washington D.C. area to be named at a later date. This briefing will consist of a presentation of study highlights and will specifically address findings, conclusions, and recommendations for management action based on the findings. The contractor will also be prepared to discuss its potential implementation

6.0 PLACE OF PERFORMANCE

The contra[illegible] tasks shall be accomplished at the place that the contractor con[illegible]rs most apr[illegible]oriate. The contractor [illegible] expected to travel as nec[illegible]ary to [illegible] key industry and g[illegible]nment officials as required by this statement of work [illegible] [illegible]s unsol[illegible]ited proposal.

FIGURE III (continue)

Correspondence is an important part of the daily workload. External and internal letters and reports represent the Center and can portray a positive or negative image. The final copies are the responsibility of the GS-6 and the GS-4. The director and research managers dictate or make notes for their letters and reports. The GS-6 composes much of the routine correspondence as time permits and the urgency of the item demands, the communications are prepared.

The logging or tracking procedures for proposals, projects, and mail is handled by the GS-6. This procedure is the only one the office maintains as a check on time schedules and number of proposals and projects. The GS-6 devised the forms for this process.

The telephone is a necessary communication tool, but as in all business offices, answering and handling telephone calls consumes valuable time. Answering the telephone is the responsibility of the GS-6 and the GS-4. Three lines are maintained by the Center and the load of incoming and outgoing calls are heavy. The average number of incoming calls per day is twenty-five.

The Southeastern Conference for Electrical Engineering Education summer faculty program which is sponsored by the Office of Scientific Research is a research program with which the AFBRMC is affiliated. During the summer of 1980, four researchers were assigned to the Center for a ten-week period. This program involves a three-day orientation in the spring, provision of housing, and other support as needed during the ten weeks. A research manager is assigned to administer the program and the director and other research managers tender support in their areas of expertise. The clerical work generated by the faculty is processed by the GS-6 and the GS-4.

To help accomplish their objectives of enhancing the Center's public image, the director and research managers visit universities throughout the nation. The visits provide visibility to AFBRMC as well as encouraging academicians to review the Topics Catalog and submit quality proposals on identified needs.

The research managers and secretaries provide support and assistance to the twelve active duty reservists that are assigned to the AFBRMC as well as to other reservists who might be called upon to provide assistance. (In the summer of 1980 there were a "large" number of helpers).

Miscellaneous occurrences include receiving visitors, filling requests from other military offices, maintaining good public relations; replenishing office supplies; filling out necessary military forms--leave, TDY, transfer, travel; scheduling luncheons and other office functions.

Information Management

Information management can be described as the combining of technology and methodology with an understanding of human factors to increase the efficiency and effectiveness of office workers. Technology alone will not provide the answer. Management knows that all employees are only as effective in their job performance as their level of knowledge permits them to be, but this axiom takes on new meaning when word processing is involved because of equipment costs and necessary emphasis on quality of work. When an office acquires an expensive text-editing machine, the originator and the operator must work as a team to produce top quality documents as people and equipment represents a major investment for the organization.

The word processing equipment used by the AFBRMC is a CPT-8000 system and three selectric typewriters. The CPT is a text-editing machine which is equipped with memory and storage capacity. It has a video-display screen with fullpage presentation, a keyboard, and a printer. Using this type of equipment, a secretary can modify a document without having to retype hard copy. Five dictating machines complete the inventory of office equipment.

The GS-4 operates the CPT system; the other staff members provide the input. The GS-6 has a selectric typewriter; the student workers use the other two typewriters.

Communication

As in any organization, communication is an integral part of the AFBRMC. It is the process by which information is transmitted and received, and the success of the Center depends on how effectively the staff communicates.

Opportunities always exist to improve communication and this fact is also true about the AFBRMC. Three Air Force publications--"U.S. Air Force Effective Writing Course," "Guide for Air Force Writing," and "The Tongue and Quill"--are available for the staff to use as references and to refresh their communication skills. Everyone should periodically evaluate her/his own writing; people become complacent about their communication skills and when this attitude exists, miscommunication often occurs.

IV. CONCLUSIONS

This study was initiated by the researcher with the approval of the Executive Director of the Air Force Business Research Management Center (AFBRMC). All information in this study is to be directed to and handled by the Center. Recommendations are to be reviewed by the Director and action taken as he deems appropriate.

Management and Productivity

The Advisory Board provides guidance and direction to the AFBRMC at the semiannual meetings. At the summer meeting valuable input was provided to the Center. The members of the Board were receptive to most of the Center's ideas and plans. The concensus of the AFBRMC, as expressed in interviews with the researcher, was that this meeting was very productive. The staff felt that the members had given them concrete suggestions and meaningful direction for the coming year. The researcher appreciated the free flow of information between the staff and the board, and the smooth transition as the various topics were considered. She was of the opinion that the meeting was effectively and efficiently conducted.

The Executive Director of the AFBRMC is a theory "Y" manager, and given the nature of the work and the caliber of the personnel, the Center operates more productively with an unstructured and flexible atmosphere. Comments made by the staff indicated that they appreciated the Director's sensitivity and his display of interest in them and his concern for their welfare. The Director believes that employees work at their own pace in fulfilling the obligations and responsibilities of their positions. His expectations of the staff are high and they perform accordingly.

> "Treat people as if they ought to be, and you will help them become what they are capable of being." Johann W. Von Goethe

During the past year, in addition to the responsibilities and duties as outlined in AF 1378, the Director has written and published six articles, read two papers, and attended various conferences and symposiums. He is president-elect of the local Rotary Club and maintains membership in other civic and professional organizations. He is well read in the acquisition area as well as in research and current events.

While conducting her interview, the researcher found that the Director was appreciated and respected by the AFBRMC staff. The Director is a strong leader and a good manager.

The research managers at the Center have a substantial workload. In addition to duties and responsibilities assigned in AF 1378, each person is allotted various administrative tasks--voting officer, equipment officer, campaign officer, etc.

The research manager positions were not fully staffed during the summer of 1980. One research manager was transferred in May, one was accidentally killed in June, and one position had been vacant for 12 months because a qualified person had not been located. Two research managers were on duty; one was being transferred August 8. However, the researcher did interview three research managers.

Of the three managers interviewed, two thought a time management program would be beneficial to the Center and that identifying and setting priorities was essential for the continued success of the organization. The other manager did not offer any input. As a result of the comments made by the research managers and after a conference with the Director, a self-evaluation program was established for time management. Each staff member was encouraged to set their daily priorities and to maintain a daily time log for a minimum of one week; maximum of two. The results of this program were to be evaluated daily by each person so that he/she could determine how time was being spent and if priorities were being attained.

The researcher is of the opinion that the time management program will increase the awareness of the importance of time and of self-discipline. These two items need to be highlighted in the informal and unstructured environment that prevails at the AFBRMC.

Productivity in the Center can be enhanced if the research managers, as originators of information, understand the capabilities and limitations of the CPT-8000 through a more thorough familiarity with the basic machine functions. When the system's operator and the originators work as a team, the process will flow more smoothly and as a result, the organization will benefit from increased productivity.

Since four of the five research managers have been on staff for two weeks or less, the conclusions on the productivity of the managers cannot be validated. The experienced manager was a hard worker and totally dedicated to his work, the Center, and the Air Force. He worked long hours, evidenced technical knowledge, and had a wide range of personal contacts. The researcher ranked him high in productivity.

The GS-6 and the GS-4 are among the most productive clerical workers with whom the researcher has had the privilege of working. All other areas of the office staff, the Director, Research Managers, Copper Cap, and summer faculty, paid tribute to the quality and quantity of work produced.

The GS-6 has been with the AFBRMC since its inception. Her interest and professional ability are exceptional. She has administrative and managerial abilty; the forms that she designed for the Center and the tracking procedures that she instituted are examples. The Air Force and Civil Service should recognize her potential and provide her with the necessary incentives to continue in their service. Her efficient organization of the office routine makes her highly productive.

The GS-4 position consists of two half-time employees. The two people are equally qualified and equally productive. Little time or effort is lost in the transition from one person to another. The GS-4s operate the CPT-8000. The word processing system is their responsibility; and in order to use the system to the best advantage, the operators and the system need the support and understanding of the originators. If constructive criticism is given, the criticism is accepted as it is intended. The pleasant personalities of the GS-4s help maintain the congenial atmosphere in the Center. They can produce a 20-page report in half a day while answering the telephone, greeting visitors, and handling requests for information. The quality and quantity of work produced by the GS-4s is high.

The Copper Cap continued his acquisition and procurement training at the AFBRMC by providing needed support to the staff. During June 1980 a research manager was accidentally killed and the trainee was asked to continue his services at the Center and fill the vacant position until October. His original departure date was 15 June 1980. The Copper Cap agreed to assist the AFBRMC in any way that he was needed. He assumed responsibilties for the deceased manager's projects which included conferring with researchers, holding briefings, providing support information and facilities, etc. The Copper Cap trainee also assumed the duties of the research manager at the summer board meeting. In the opinion of the researcher, the Copper Cap is due the salute, "Performed above and beyond the call of duty."

The trainee is a bright young man who works well under pressure. He is pleasant and maintains a friendly relationship with other personnel. He is highly productive.

The student workers are under the supervision of the GS-6. She assigns the work as assistance is needed. These positions are training positions and provide a learning experience for the students. The two are very pleasant and cooperative.

Information Management

The CPT system is not used to its full capacity. The flow of information in the office is not properly organized; consequently, many of the special features of the unit are not utilized. With the addition of the compatible unit, the system will be more efficient. The research managers should know the basic operation of the machine so that they can work cooperatively with the operators to produce quality output. Responsibility and duties that require the operator to be away from the system reduce productivity. Better organization of the information at AFBRMC would help increase productivity.

Communication

In evaluating the written communication at the Center, the researcher found most of it to be effective. One item that is produced by the AFBRMC which could be improved is the Acquisition Research Topics Catalog. During conversations with members of the OSR summer faculty, the members indicated that a better understanding concerning the identified needs between the Center and the academic world could be established if the acquisition vocabulary and the academic vocabulary could be matched, and this information included in the Catalog.

Although not exclusively a problem of AFBRMC, the use of acronyms and abbreviations in government and military documents and in the oral communication at government and military installations should be reviewed. The widespread use of these symbols causes difficulties for anyone who is unfamiliar with the jargon. How much miscommunication is caused by the use of acronyms?

The AFBRMC is a highly productive office. However, because of its important work in the research arena, the researcher has several recommendations that might add to the productivity of the Center.

RECOMMENDATIONS

This study indicated that research is needed in the area of white-collar productivity as it relates to effective communication. In evaluating the AFBRMC, these areas for further study were identified: increased effectiveness in the use of the word processing equipment, the effect of acronyms on communication, and improved management of information. The studies could be funded by grants from the Office of Scientific Research.

1. A time-management log should be kept by all members of the staff for a period of one to two weeks. Priorities should be set each day, and an assessment made at the end of the day.
2. An Administrative Assistant should be added to the staff of the AFBRMC. This position is needed to relieve the Research Managers of their administrative duties. When relieved of these duties, the research managers will be able to devote more time to the research areas. The Administrative Assistant would enable the Center to operate at a higher level of productivity by providing management support.
3. Originators of information should be acquainted with the capabilities and limitations of the CPT system. Perhaps a company representative could conduct a training session for all originators. Periodically, the originator should review the operating manuals so that basic information can be updated.
4. A tracking-systems chart for funded proposals should be displayed in the office.
5. Priorities on the five major workload projects need to be determined. A work schedule should be devised and followed. This schedule should be posted and routine work scheduled around the projects.
6. The Administrative Assistant, if the position is approved, should be provided with a correcting, Selectric II typewriter.
7. A video-recorder would facilitate orientation for new staff members, summer faculty, and student workers. This equipment would also enhance public relations during staff visits at university campuses.

8. A compatible unit to the CPT-8000 should be provided for the GS-6. The addition of this unit combined with the suggestions in the conclusions should increase equipment time. Further study in this area is warranted.
9. Improved use should be made of the dictating equipment. Optimum use of this equipment would add to the efficiency of the word-processing system. Additional research in this area could aid in increasing productivity in the office.
10. The Acquisition Research Topics Catalog is difficult for members of the academic community to understand. The vocabularies of the two areas are very different. The recommendation is that an array of academic and acquisition terms be constructed into a matrix for inclusion in the Catalog.
11. Communication in the government and military communities is being encroached upon by the use of acronyms. Effective oral and written communication is hindered by the over use of these symbols and a mini grant should be awarded to conduct a study to determine the effect that acronyms have on communication.

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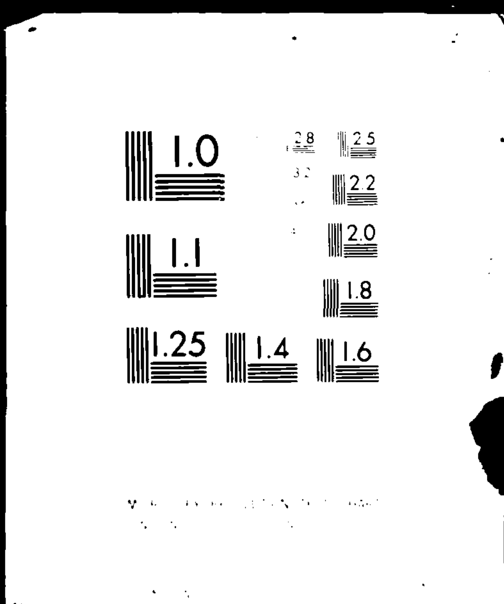

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FINAL REPORT

RESPONSE SURFACE FITTING FOR MISSILE ENDGAME MODELS

Prepared by: Stanley H. Benton, Jr.

Academic Rank: Associate Professor

Department and University: Computer Science Department, Tulane University

Research Location: Armament Division, Missiles and Guns Analysis Branch (DLYD), Eglin AFB FL

USAF Research Colleagues: Mr. Carson W. Sasser
Mr. Patrick C. Coffield

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RESPONSE SURFACE FITTING FOR

MISSILE ENDGAME MODELS

by

Stanley H. Benton, Jr.

ABSTRACT

To eliminate some of the high cost of running typical air-to-air missile endgame programs, some sort of surface fitting is desirable. In theory, this is simply a problem of fitting a real function of several real variables to a collection of data points. However, the data leads to functions with steep rises and large flat areas, suggesting exponential functions with their corresponding numerical difficulties in fitting. It was determined that such a fitting process is feasible, but that further work is needed in the areas of design of the experiment and optimization methods.

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The author is particularly indebted to P. C. Coffield for his patient instruction on his SHAZAM endgame program, C. W. Sasser and Dr. Donald C. Daniel for smoothing his administrative tasks, Capt. G. W. Keethler for his detailing of his earlier work, and Lt. Tommy Smith, Mr. William Shirley, Mr. Hal Smith, Mr. Richard Strickland, Ms. Judith Stokley, Mr. Aaron Brinson, and numerous other members of DLYD for their assistance in technical matters, particularly with respect to the computer system in use at Eglin AFB.

I. INTRODUCTION

Computer programs to predict kill probabilities for air-to-air missile endgame problems are typically very cumbersome and time consuming to run. Thus for many applications it is desirable to use some fitting technique to approximate the output of the endgame program quickly and cheaply. Capt. G. A. Keethler, in his AFIT Thesis (9) had excellent results with such a fitting method. However, his techniques were not broken completely into algorithms, hence could not be automated directly. His sample space for fitting was also somewhat restricted, and included no effects of missile elevation relative to the target. Thus less restrictive geometric inputs to the fitting method are desired. For more background information on endgame problems, see the Keethler report.

Because of Keethler's success in modelling the endgame program, SHAZAM, of P. C. Coffield of AFATL at Eglin AFB, it was decided to sponsor a ten-week further study by this author, under the AFOSR/SCEEE Summer Faculty Research Program. This report is a brief summary of the results of the ten-week study.

The study indicates that good fits can be obtained, but that further analysis may be desirable to design an experiment to cover the whole space of input parameters more uniformly, and to test alternate fitting functions for possible increases in speed or accuracy. More sophisticated optimization methods may also be desirable for the fitting process. The procedure outlined in this report is completely automated, with modular computer programs, written in FORTRAN IV, stored on the Eglin Timesharing System.

II. OBJECTIVES OF THE RESEARCH EFFORT

As outlined in the introduction, the objectives of the research effort were to generalize and automate the surface fitting methods of Capt. Keethler, and of course to test the feasibility of such an approach in the first place. The real problems concern the suitability of the data for such methods, rather than theoretical considerations. Thus computer programs had to be developed at each stage of the process, and the data manipulated by computer.

III. TEN-WEEK STUDY

Most of the details of the Keethler study will be omitted from this report. It is suggested that the reader might peruse the Keethler report before continuing here, should a better feeling for the history and background be desired. Our study began with a complete review of the Keethler report, together with its included references, particularly those relating to design of experiments and response surface technology. Then a fairly complete search of the more current literature was undertaken.

Mechanical fits for the pulse-like curves of the Keethler method were developed. These curves resulted from plotting the kill probability (P_k), against the position along the relative trajectory of the missile detonation (burst) point. This position is called "X_M" in both the Keethler study and the SHAZAM program. Thus with all other geometric factors fixed, P_k vs. X_M yields a pulse resembling a slightly rounded square pulse, sometimes with a dip in the top. Keethler fit a function of the form

$$P_k = e^{-\left|\frac{X_M+A}{B}\right|^6} \tag{1}$$

The three methods of mechanizing the fitting process are described in Appendix 1.

For inclusion of the other geometric factors, there are two possible approaches. The first is: fit an equation (1) for each combination of factors to be considered, then fit some sort of curves to A and B [of (1)] as functions of the other factors. The second is: decide on the form of A and B as functions of the other factors first, then fit A and B in (1) as functions of all factors, including X_M, simultaneously. Either method has some advantages, and could be persued. Because of a lack of time, only the second method was used for this study.

More fundamental geometric factors were desired to use as independent variables in the fitting process. Thus the SHAZAM geometry was studied, and six factors, which summarize the relative speed, position, and attitude of the target with respect to the exploding warhead, were chosen. The pertinent geometry and fundamental factors are described in Appendix 3.

It was decided to fit a slightly more general function than (1). Thus we selected

$$P_k = Ce^{-\left|\frac{A}{B}\right|^{D}}, \qquad (2)$$

where A, B, C, and D are all functions of the six fundamental factors. The functions chosen were fairly complicated, allowing consideration of a total of 312 undetermined coefficients. See Appendix 4 for a complete description of the fitting function.

The root mean square error in the fitted P_k's [versus the SHAZAM-generated (true) P_k's] was used as a goodness of fit criterion. This error was minimized as a function of the coefficients by the gradient method. See Appendix 2. See also Fleming (7) and Saaty & Bram (11), for further information on the gradient method.

The original plan was to design an experiment (choose data points), in the space of the six fundamental factors, then run SHAZAM for inputs corresponding to the chosen data points, thus obtaining P_k's. The data points and their corresponding kill probabilities would then be used to determine the unknown coefficients involved in equation (2). Equation (2), with A, B, C, and D given by the fit functions, would then constitute the approximating model to SHAZAM (with the given missile and target model in SHAZAM). For other warheads, or target models, the whole process would be repeated. Thus one equation (2) would correspond to each warhead-target combination. In addition to equation (2), there is one additional step necessary to model SHAZAM. Although the directions of relative velocities, and target attitude are inputs to SHAZAM, the radial miss distance coordinates are treated as random variables. SHAZAM uses a Monte Carlo technique to approximate the integration of the probability density function involved. The Keethler study utilized the well known 109 cell model to do this integration, thus saving a large amount of computer time. Thus the 109 cell model, in conjunction with a transformation to the fundamental factors and equation (2), constitutes the model of the fragmentation-kill mode portion of SHAZAM. The blast-kill and direct-hit-kill portions of SHAZAM are simple and fast, so are retained in the simplified model.

Because of the cost of running SHAZAM, it was decided to test the scheme first by using data furnished by G. A. Keethler. This data included 332 data points, and associated SHAZAM-generated values of P_k.

Of course this data did not constitute a nicely balanced coverage of our fundamental factor space. The fitting procedure was followed, and the RMS error,

$$RMS = \left\{ \sum_{\substack{\text{all data} \\ \text{points}}} \left(P_k - Ce^{-\left|\frac{A}{B}\right|^D} \right)^2 \bigg/ \left(\#\text{data points} \right) \right\}^{1/2} , \qquad (3)$$

minimized. A RMS of about 0.2 was obtained using only 40 undetermined coefficients in (2). Although this seemed a little high, the Keethler error analysis of the 109 cell model indicated that it might be satisfactory. Keethler also supplied extra data that he had used to test his fits. This data (about 150 data points) was used as input to the 109 cell model with equation (2). The resulting P_k values were uniformly within the 0.1 confidence interval yielded by the SHAZAM program, indicating quite satisfactory fits. The graphs of two groups of these data points, with only X_M varying, are included as Figure 1 and Figure 2. The Keethler parameters are included on these figure only as identification, and to allow comparison with the same data in the Keethler report, hence will not be described in this report.

The whole procedure is mechanized, and a brief summary of the programs is included in Appendix 5. The procedure followed is, briefly:

1. Obtain data points described in the Keethler parameters.
2. Run SHAZAM to generate associated P_k's.
3. Combine the data points and the P_k's on one file.
4. Run SBGEOM to generate the fundamental factors.
5. Run SBFIT: one iteration in mode 1 to obtain starting values (coefficients), 40-50 iterations in mode 2 to introduce 30-40 non-zero coefficients, 100 iterations in mode 3 to optimize RMS as a function of the non-zero coefficients.
6. Run SBINTEG for additional data points to perform the integrations (109 cell model), and test the fits.

As already pointed out, Keethler-supplied data eliminated the need for steps 1 through 3. Further studies should start with either SHAZAM variables, or fundamental factors, eliminating step 1 completely. However, lack of time prevented us from going further during the ten week study.

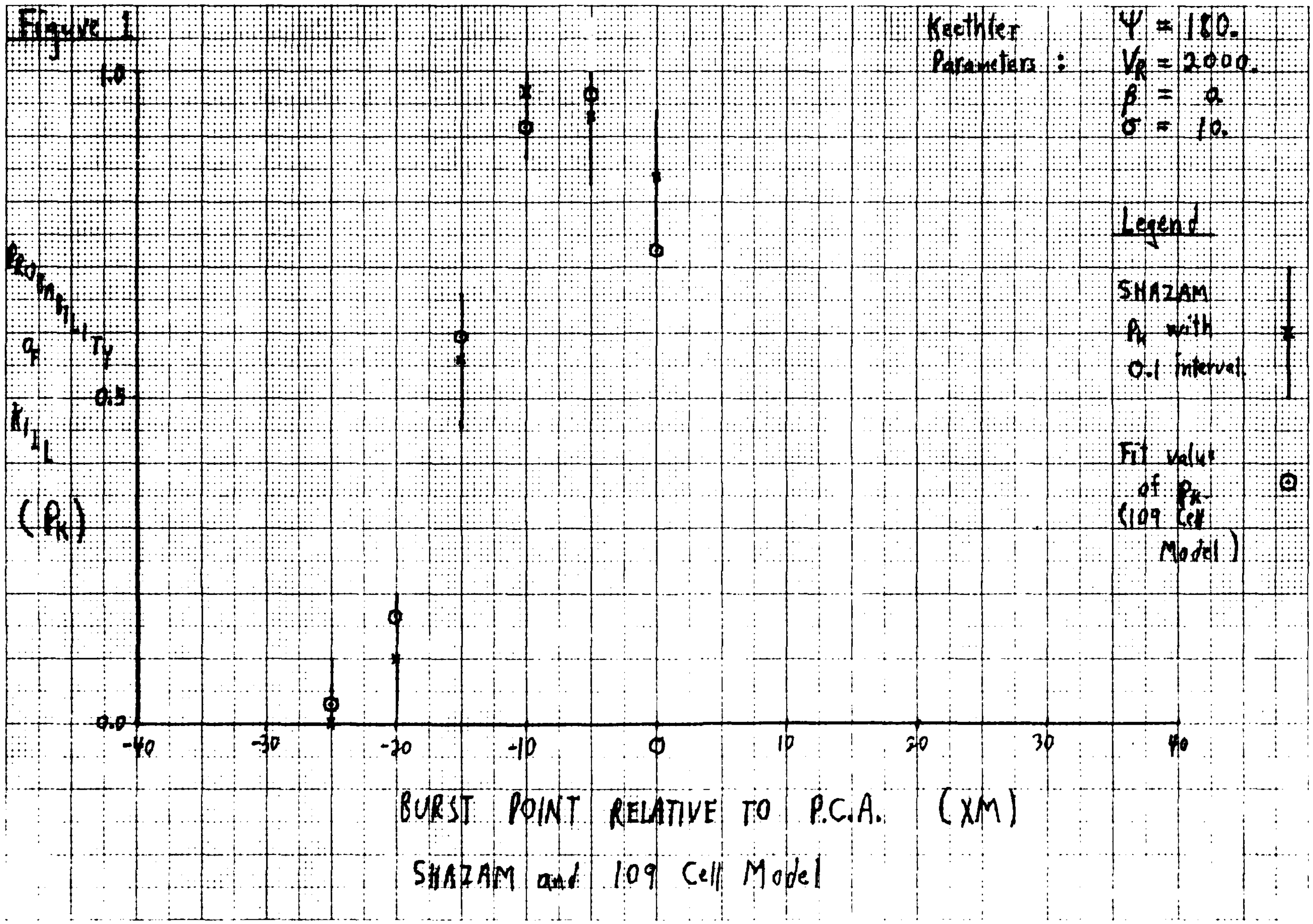
Figure 1
Kaethler Parameters :
Ψ = 180.
V_R = 2000.
β = 0.
σ = 10.
Legend
SHAZAM P_K with 0.1 interval
Fit value of P_K (109 Cell Model)
Probability of Kill (P_K)
1.0
0.5
0.0
-40
-30
-20
-10
0
10
20
30
40
BURST POINT RELATIVE TO P.C.A. (XM)
SHAZAM and 109 Cell Model

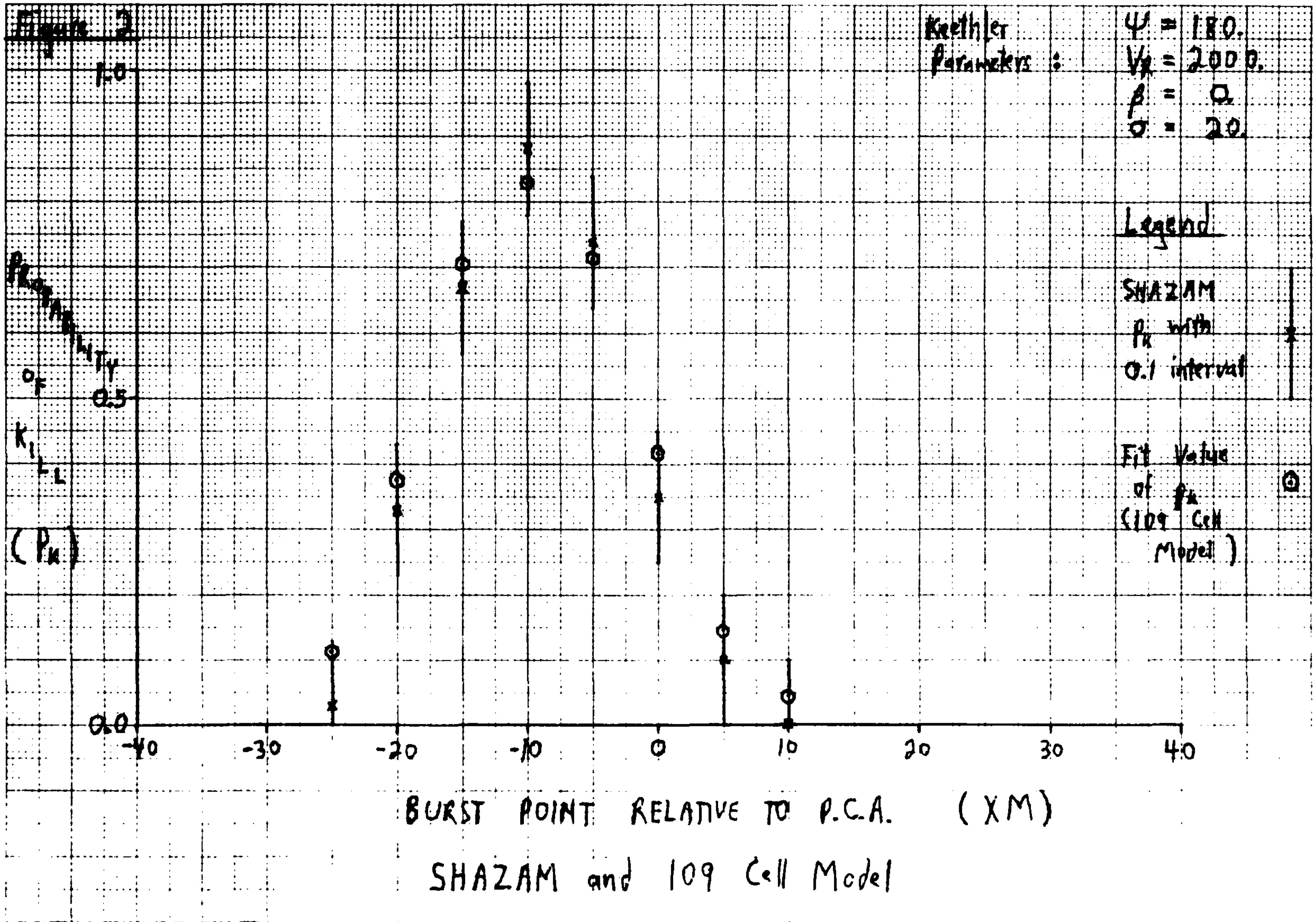

Figure 2
Keethler Parameters :
Ψ = 180.
Vk = 2000.
β = 0.
σ = 20.
Legend
SHAZAM Pk with 0.1 interval
Fit Value of Pk (109 Cell Model)
Probability of Kill (Pk)
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-20
-10
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10
20
30
40
BURST POINT RELATIVE TO P.C.A. (XM)
SHAZAM and 109 Cell Model

IV. SUMMARY

The fitting technique promises good results. However, further work might be desirable in the areas of:

1. Design of the experiment,
2. Selection of SHAZAM variables from fundamental factors,
3. More efficient optimization of the fit,
4. Simpler (and thus faster) fitting functions,
5. Sensitivity to changes in warhead and target models.

V. RECOMMENDATIONS

1. The results of this research may be implemented by following the steps outlined at the end of section III.

2. Although the results outlined earlier were promising, even better fits were obtained using the full 312 coefficients, and some promise was shown for a simple quadratic polynomial. Thus further testing as outlined in the summary may be desirable.

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Appendix 1. Curve Fits for Pulse-Type Data

To fit a curve to data which approximates a slightly rounded square pulse, we have chosen a function of the form:

$$y = Ce^{-\left|\frac{X+A}{B}\right|^{D}} \tag{1}$$

Three different curve fitting techniques were tested, as discussed in the body of this report. These three techniques are: linear regression, maximum likelihood estimation, and full least squares. For each of the three methods, we assume given n data points, all normalized so that all ordinates lie between zero and one. Let (x_j, y_j), j=1, 2, ... n represent these points.

Method 1. Linear Regression

To use a standard linear regression, we must fix C=1 and D=6, as in the Keethler study [9]. We then make the transformation:

$$Z_j = \text{sign } (X_j-\mu)\ (-\ln y_j)^{1/D}, \tag{2}$$

where $\mu=-A$, then fit

$$Z = a + bx, \tag{3}$$

where B=1/b, A=a/b.

This standard linear regression may be completed by solving the normal equations:

$$\begin{pmatrix} n & \Sigma X_j \\ \Sigma X_j & \Sigma X_j 2 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} \Sigma Z_j \\ \Sigma Z_j X_j \end{pmatrix}, \tag{4}$$

where each summation is for j ranging from 1 to n.

There are two problems with this approach. First, for our problem, several of the y_j are zero, so that z_j cannot be defined in any reasonable manner. Thus we ignore these points and reduce n accordingly. The second problem is that $\mu=-A$ is not known beforehand, so that sign $(x_j-\mu)$ is unknown. This problem is handled by ordering the x_j, then assuming that the first k of the x_j are less than μ, the rest greater. The choice of k comes by estimating μ (say as the mean of the x_j). The linear regression is completed, then k incremented and the whole process repeated. The k yielding the best fit to the original data with no inconsistencies is chosen for the final fit.

The above method was used to fit curves to data furnished by G. A. Keethler, with root mean square errors of 0.25 to 0.35 occurring on typical pulses of from six to ten data points.

Method 2. Maximum Likelihood Estimation

The usual usage of maximum likelihood estimation is to assume a distribution, usually normal, for the errors, then to choose the parameters so as to optimize this distribution according to predefined criteria. However, for pulse-type data, or any curve with finite area for that matter, a simpler method may be used. We assume simply that the curve itself is a frequency distribution. Thus let

$$f(X;A,B) = Ke^{-\left|\frac{X+A}{B}\right|^{D}} \tag{5}$$

where C=1, D=6 as before, and K is a normalization factor. (If D were 2, K would be $\frac{1}{\sqrt{2\pi B}}$, and we would have a normal distribution.)

Treat the actual data, multiplied by some large constant M, as a "number of occurrences". The likelihood function is thus

$$\mathcal{L}(A,B,M) = \prod_{j=1}^{n} \left(Ke^{-\left|\frac{X_j+A}{B}\right|^{D}} \right)^{My_j}$$

$$= K^{\sum My_j} \cdot \exp \sum \left\{ -My_j \left| \frac{X_j+A}{B} \right|^{D} \right\} \tag{6}$$

Since $\int_{-\infty}^{\infty} f(X:A,B)dx = 1$ it can be shown that K is a function of D, divided by B. That is,

$$K = \eta(D) / B. \tag{7}$$

Maximizing $\mathcal{L}$ is equivalent to maximizing $\ell = \ln \mathcal{L}$. Equating $\frac{\partial \ell}{\partial A}$ to zero yields:

$$\sum y_j (X_j+A)^{D-1} = 0. \tag{8}$$

After solving (8) by any root finding method (Newton's method works quite well here), B may be found directly by equating $\partial\ell/\partial B$ to zero, obtaining

$$B = \left\{ \frac{\sum y_j (X_j+A)^{D}}{\sum y_j} \right\}^{1/D} \tag{9}$$

This method was also used to fit curves to the Keethler data, with root mean square errors of 0.2 to 0.3 on typical pulses.

Method 3. Full Least Squares

This method is the most straightforward of the three, and certainly yields the best fits, but leads to much more computational difficulty. Allowing C and D to vary, as well as A and B, we form the error function:

$$E = \sum \left\{ y_j - Ce^{-\left| \frac{X_j + A}{B} \right|^{D}} \right\}^2 \tag{10}$$

This function is then minimized by whatever method is desired. We choose the gradient method, obtaining root mean square errors (RMS = $\left\{E/n\right\}^{0.5}$) on the order of 0.1 after ten to twenty iterations.

Appendix 2. The Gradient Method

One method of minimizing a real function, e, of n real variables, is the gradient method, or "steepest descent". This is an iterative method which has great generality, often producing satisfactory results even though the function involved is quite misbehaved. However, the method is often very slow in converging, and may be expected to lead to local, but not global, optimums in all but particularly fortitous circumstances. See Fleming [7] for related theorems.

This method consists of choosing an initial point, X_o, in R^n, then finding a direction in which to move away from X_o to a new point X_1 such that $e(X_1) < e(X_o)$. Since the direction of maximum increase in e is the gradient vector $\nabla e(X_o)$, the point X_1 is chosen to be:

$$X_1 - X_o - \lambda \nabla e\,(X_o), \tag{1}$$

where λ is a positive real number. That is, the movement is opposite to the direction of the gradient. The process is repeated until the gradient becomes small enough to be considered to be zero, or until X_1 is so close to X_o that the convergence criteria are met.

Assuming a complicated function e, the gradient method consists of solving two problems: the estimation of $\nabla e(X_o)$, and the choice of λ.

The Estimation of $\nabla e(X_o)$

The assumption is made here that the function e is sufficiently complicated that analytic computation of $\nabla e(X_o)$ is undesirable or impossible. There are many numeric methods for the estimation of the partial derivatives. However, if e is difficult and expensive to calculate, a simple method requiring a minimal number of evaluations of e is desirable. Since the actual gradient direction is not too critical in this method, with inaccuracies causing at worst slower convergence, sophisticated evaluation of $\nabla e(X_o)$ is not necessary. Thus we have selected a simple difference; a real $\delta > 0$ is chosen, and the partial derivatives are estimated by

$$\frac{\partial e}{\partial X_j} \approx \frac{e(X_o + \delta E_j) - e(X_o)}{\delta} \tag{2}$$

where X_j is the jth component of X, and E_j is the unit vector along the X_j-axis.

For a function e which is not too well mannered, having no derivative at places, or not defined past some boundary, equation (2) can indicate a positive derivative, causing eventual movement in the opposite direction which actually produces an increase in e. The canonical example is the absolute value function of one real variable, $e(X)= |X|$, at $X=0$. Strictly speaking, the gradient method can not handle this situation. However, the method may be modified by using $-\delta$ in place of δ in equation (2) for components for which (2) gives a positive value. Should both δ and $-\delta$ lead to an increase in e, the partial derivative for that component can set to zero.

The Search for λ.

The gradient, $G=\nabla e(X_o)$, gives the direction in which to move, and λ tells one how far to move. Were this the best of all possible worlds, one could determine

$$f(\lambda) = e(X_o-\lambda G) \tag{3}$$

analytically, equate $f'(\lambda)$ to zero, and obtain the best λ to use [for minimum $e(X_1)$]. Given that this procedure is not feasible, some searching technique must be chosen to find a decent λ, although not necessarily the optimum value. If it is known that e is convex, with minimum value zero, a linear extrapolation to the place e=o, as in the secant method for one variable, sometimes yields good results. That is, $\lambda=e(X_o) / \|G\|^2$. One other variation consists of allowing λ to become "infinitessimal", obtaining a differential equation $X'(\lambda)=\Delta e[X(\lambda)]$. The limit of the solution, X, of this equation, as $\lambda\to\infty$, yields the desired local optimum (hopefully). But most functions e require a brute force search, probably a binary search of some type. We have chosen a method which generally requires only three evaluations of e to determine λ, but produces a satisfactory (but not optimum) value of λ. This search procedure is described below.

Let $$\lambda_1 = \delta / \|G\| . \tag{4}$$

By choosing this λ_1, the movement from X_o to X_1 has magnitude , and, since δ was used in estimating the gradient, it is very likely that a movement of this size actually produces a decrease in e. If not, that

is, $f(\lambda_1) \geq f(0)$, replace λ_1 by $\lambda_1/2$. Repeat this halving procedure until $f(\lambda_1) < f(0)$. Should the halving lead to no acceptable λ_1, halve δ and reestimate G. If no δ-λ_1 combination succeeds in producing $f(\lambda_1) < f(0)$, the method fails. Assume now that $f(\lambda_1) < f(0)$.

Let $\lambda_2 = 2\lambda_1$. If $f(\lambda_2) - f(\lambda_1) \leq f(\lambda_1) - f(0)$, replace λ_2 by λ_1 and repeat. (This is good, it just yields a better value of λ_1). Assume now that

$$f(\lambda_2) > 2f(\lambda_1) - f(0). \tag{5}$$

We may now fit a parabola through the points: $[0, f(0)]$, $[\lambda_1, f(\lambda_1)]$, and $[\lambda_2, f(\lambda_2)]$. Relationship (5) ensures that the fit parabola opens upward, so has a minimum value. This minimum point yields a λ-value, which we call λ_3. See figure A2.1. The final λ selected is whichever of λ_1, λ_2, and λ_3 yields the minimum value of e.

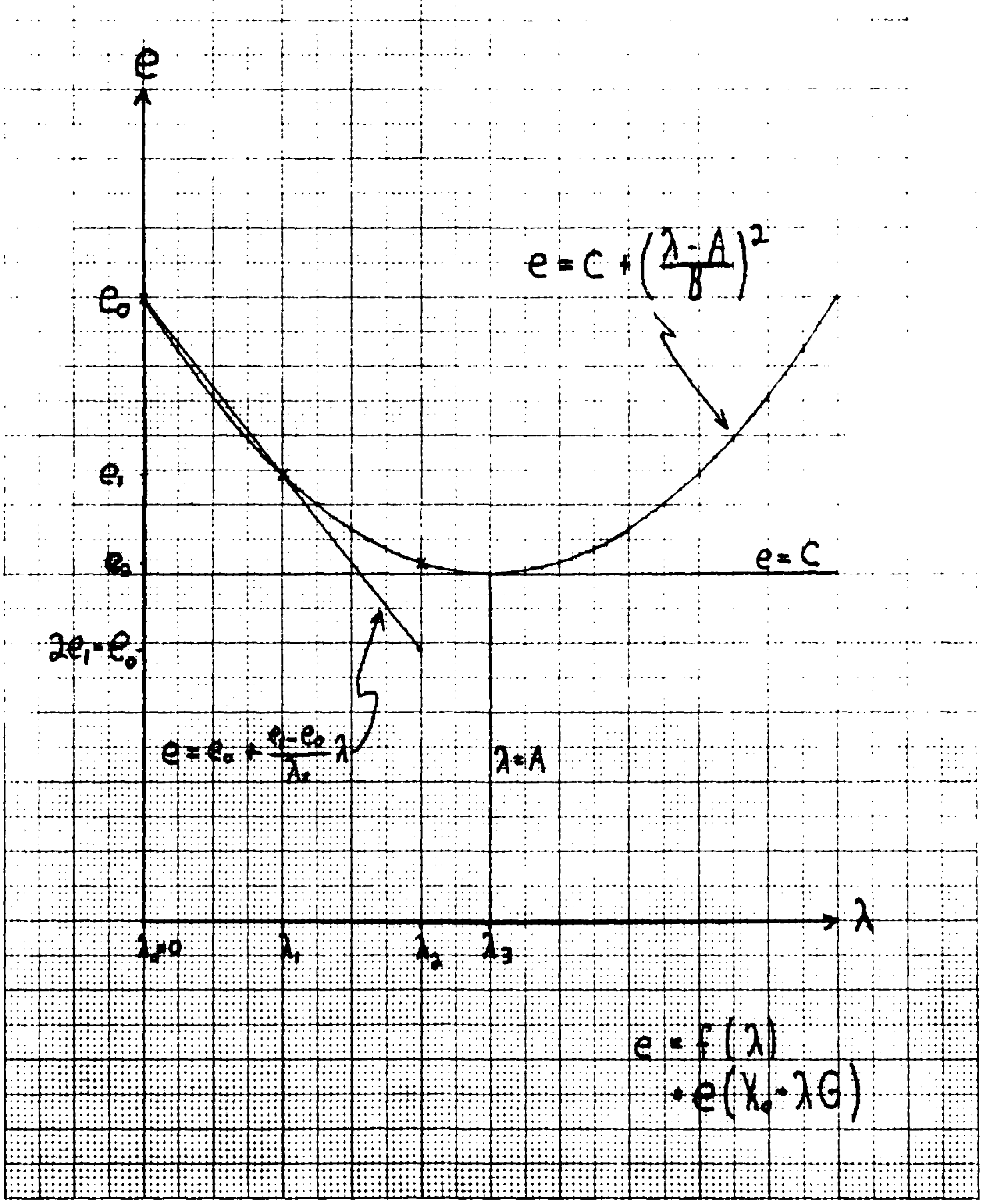
To obtain λ_3, assume that

$$e = C + \left(\frac{\lambda - A}{B}\right)^2 \tag{6}$$

Substituting the given points in (6), setting $e_i = f(\lambda i)$, $i=0,1,2,\lambda_o=0$, and solving for A yields

$$\lambda_3 = \frac{\lambda_1}{2}\left\{2 + \frac{e_2 - e_0}{(e_1 - e_0) - (e_2 - e_1)}\right\} \tag{7}$$

Figure A2.1
Typical Plot of f(λ) vs λ
Including Parabolic Fit for λ3.



Appendix 3. Geometric Considerations

This appendix will describe the coordinate systems and transformations used in the SHAZAM endgame program, and the fundamental geometric factors chosen as independent variables for our surface fitting method. We begin with a brief review of rotation matrices.

Rotation Matrices

Suppose we are given a standard right handed coordinate system for three dimensional Euclidean space, consisting of unit vectors I, J, K. Any three vector, V, may be represented as

$$V = aI + bJ + cK, \tag{1}$$

where a, b, and c are real numbers. Thus V is usually identified with the column vector of coordinates:

$$V = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \tag{2}$$

Now if all vectors are free vectors (direction only is considered, not point of application), any other standard right handed coordinate system may be obtained from the first by a rotation. Thus suppose that I', J', K' determine another system. Then if V in (2) is given by $V' = (a', b', c')^t$ in the second system,

$$V' = T\,V, \tag{3}$$

where T is a three by three orthogonal matrix with determinant equal to +1, called a rotation matrix.

Letting $V = I = (1,0,0)^t$, we see that

$$V' = \begin{pmatrix} I \bullet I' \\ I \bullet J' \\ I \bullet K' \end{pmatrix} \tag{4}$$

and, performing the matrix multiplication in (3), we see that the vector in (4) is the first column of the matrix T. Similarly letting V=J, then K, we find

$$T = \begin{pmatrix} I \bullet I' & J \bullet I' & K \bullet I' \\ I \bullet J' & J \bullet J' & K \bullet J' \\ I \bullet K' & J \bullet K' & K \bullet K' \end{pmatrix} \tag{5}$$

where "•" represents the "dot" or "scalar" product.

Usually the components of one coordinate system in the other system (e.g. J•I' etc.) are not known d[illegible]ctly, but a series of simple rotations is given. We shall use a slig[illegible] modification of the standard

definition of Euler angles. Thus we think of our coordinate systems as being aircraft, with the I-vector pointed out the front, J out the port wing, and K out the top. To pass from a system we shall call "A" to a system B, we pass through two intermediate system, A' and A" by first yawing about K_A, then pitching about $-J_{A'}$, and finally rolling about $I_{A''}$.

Thus any vector, V_A, given in system A, has representation $V_{A'}$ in system A', where $V_{A'} = T_{A'A} V_A$, and

$$T_{A'A} = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

since $I \cdot I' = \cos \Psi$ and so on. (See Figure A3.1.) Similarly

$$T_{A''A'} = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \tag{7}$$

and

$$T_{BA''} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}$$

(See Figures A3.2 and A3.3.) Now since, for any vector V, $V_B = T_{BA''} V_{A''} = T_{BA''} T_{A''A'} V_{A'} = T_{BA''} T_{A''A'} T_{A'A} V_A$, one sees that

$$T_{BA} = T_{BA''} T_{A''A'} T_{A'A} \tag{9}$$

Explicitly this is

$$T_{BA} = \begin{pmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & \sin\theta \\ -\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & -\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ -\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & -\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{pmatrix} \tag{10}$$

Note that $T_{AB} = T_{BA}^{-'} = T_{BA}^{t}$, the transpose of T_{BA}.

SHAZAM Geometry

In the SHAZAM endgame program, there are five coordinate systems of interest to us. They are summarized in Table A3.1.

The target velocity system is based upon the target velocity (assumed to lie in a horizontal plane), and the horizon plane. In this system, the target velocity vector is given by

$$V_T = \mathcal{V}_T \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}_V \tag{11}$$

where $\mathcal{V}_T$ is the target's speed.

System T, the Target Vehicle System, is based upon the target itself. It may be obtained from System V by a yaw of ψ_T, pitch of θ_T, and roll of ϕ_T. Thus T_{TV} is given by equation (10) with $\psi=\psi_T, \theta=\theta_T, \phi=\phi_T$.

The missile velocity vector, V_M, is given by giving $\mathcal{V}_M$, the missile speed, ψ_C, the azimuth (yaw) of the vector $-V_M$ about K_V, and γ, the elevation of $-V_M$ about the intermediate J-axis. See Figure A3.4. Thus $\psi_I=\pi+\psi_C, \theta_I=-\gamma$, and V_M is, in System V,

$$V_M = \begin{pmatrix} \mathcal{V}_M \cos\psi_I \cos\theta_I \\ \mathcal{V}_M \sin\psi_I \cos\theta_I \\ \mathcal{V}_M \sin\theta_I \end{pmatrix}_V \tag{12}$$

Once the missile velocity has been determined in System V, the relative velocity may be computed, from

$$V_R = V_M - V_T = \begin{pmatrix} \mathcal{V}_T - \mathcal{V}_M \cos\psi_I \cos\theta_I \\ -\mathcal{V}_M \sin\psi_I \cos\theta_I \\ -\mathcal{V}_M \sin\theta_I \end{pmatrix}_V = \begin{pmatrix} V_{RX} \\ V_{RY} \\ V_{RZ} \end{pmatrix}_V \tag{13}$$

The relative system may then be determined from (See Figure A3.5):

$$\psi_R = \begin{Bmatrix} \frac{\pi}{2}[1-\text{sign}(V_{RX})] + \tan^{-1}(V_{RY}/V_{RX}), \text{ if } V_{RX} \neq 0, \\ \frac{\pi}{2}\text{sign}(V_{RY}), \text{ if } V_{RX} = 0, \end{Bmatrix} \tag{14}$$

$$\mathcal{V}_R = (V_{RX}2 + V_{RY}2 + V_{RZ}2)^{0.5}, \tag{15}$$

$$\theta_R = \sin^{-1}(V_{RZ}/V_R). \tag{16}$$

Since ϕ_R is assumed to be zero, equation (10) may be simplified for this case to:

$$T_{RV} = \begin{pmatrix} \cos\theta_R \cos\psi_R & \cos\theta_R \sin\psi_R & \sin\theta_R \\ -\sin\psi_R & \cos\psi_R & 0 \\ -\sin\theta_R \cos\psi_R & -\sin\theta_R \sin\psi_R & \cos\theta_R \end{pmatrix} \tag{17}$$

To obtain the inteceptor velocity system from the target velocity system, we first yaw and pitch to an intermediate system, Vi, such that I_{Vi}, is in the direction of the missile velocity. The transformation

matrix is given by (10) with $\psi=\psi_2$, $\theta=\theta_I$, $\phi=0$. This system is then rolled through an angle of ϕ_I to bring I_{Vi} into the plane of V_M and V_T. Now V_T is parallel to I_V, and

$$I_V = \begin{pmatrix} \cos\theta_I \cos\psi_I \\ -\sin\psi_I \\ -\sin\theta_I \cos\psi_I \end{pmatrix}_{Vi} \tag{18}$$

The projection of V_T or I_V in the J_{Vi} - K_{Vi} plane is in the direction of the vector

$$I_{proj} = \begin{pmatrix} 0 \\ -\sin\psi_I \\ -\sin\theta_I \cos\psi_I \end{pmatrix}_{Vi} \tag{19}$$

The angle ν is defined from:

$$\tan\nu = \sin\theta_I \cos\psi_I \,/\, \sin\psi_I \tag{20}$$

(as long as $\sin\psi_I \neq 0$), and $\phi_I = \nu - \pi/2$. (See Figure A3.6.) Once ϕ_I is known, T_{IV} is given by (10) with $\psi=\psi_I$, $\theta=\theta_I$, $\phi=\phi_I$.

System M is obtained from System I by a pitch of θ_M so that I_M lies along the missile centerline. Thus θ_M is the missile's angle of attack, and is also called "α" in the SHAZAM program. Since yaw and roll are zero in this case, (10) reduces to

$$T_{MI} = \begin{pmatrix} \cos\theta_M & 0 & \sin\theta_M \\ 0 & 1 & 0 \\ -\sin\theta_M & 0 & \cos\theta_M \end{pmatrix} \tag{21}$$

The missile position at time of detonation, relative to the target center, is defined to be:

$$B = \begin{pmatrix} X_M \\ Y_M \\ Z_M \end{pmatrix}_R \tag{22}$$

Conversely, the position of the target relative to the missile is

$$T = -\begin{pmatrix} X_M \\ Y_M \\ Z_M \end{pmatrix}_R \tag{23}$$

Fundamental Geometric Factors

Here we treat the "fundamental factors" chosen to be the independent variables in our surface fitting model. It was attempted to find factors, independent of the coordinate systems involved, which were themselves independent, and which would express satisfactorily the speed, position, and attitude of the target with respect to the missile fragmentation pattern.

Since most fragments leave the missile at some angle which is nearly perpendicular to the centerline, relative to the moving missile, it seems reasonable to define, for purposes of parameterization, the "burst plane". This is the plane in System M perpendicular to I_M. That is:

$$BP = \left\{ X \in R^3 : X \cdot I_M = 0 \right\} \tag{24}$$

Define the point Q to be the point in the burst plane at which the target centroid will lie at some time. That is,

$$Q \cdot I_M - 0, \tag{25}$$

since Q lies in the burst plane, and

$$Q = T - d\ I_R, \tag{26}$$

for some real d, since the target travels along the $-I_R$ vector relative to the missile. Substituting (26) into (25), we have

$$d = \begin{cases} 0 & , \text{ if } T \cdot I_M = 0, \\ T \cdot I_M \,/\, I_R \cdot I_M & . \text{ if } T \cdot I_M \neq 0 \neq I_R \cdot I_M, \\ \infty & , \text{ otherwise.} \end{cases} \tag{27}$$

Once d has been calculated, one may define

$$q = \| Q \| = \| T - d\ I_R \| \ . \tag{28}$$

The quantities $\mathcal{V}_R$, d, and q are independent of each other, and sufficiently describe the target speed and position relative to the missile warhead. We now turn to a consideration of the target attitude. Define I_p to be a unit vector in the burst plane with no component "away from" the warhead. That is: $I_p = \mathcal{V} x I_M$ with $\mathcal{V} = Q/q$. Thus $I_p, \mathcal{V}$, I_M form a standard coordinate system, with I_p and lying in the burst place, I_M perpendicular to it. See Figures A3.7 and A3.8. Let I be the projection of I_T (the target cneterline direction) in the I_M-I_P plane, ε_1 the angle from I to I_T, ε_2 the angle from I_M to I. Then

$$I = I_T - (I_T \cdot \mathcal{V})\mathcal{V}, \tag{29}$$

$$\eta_1 = \cos \varepsilon_1 = \|I\|, \tag{30}$$

$$\eta_2 = \cos \varepsilon_2 = \begin{cases} I_M \cdot I/\eta_1, & \eta_1 \neq 0, \\ 0, & \eta_1 = 0. \end{cases} \tag{31}$$

The quantities η_1 and η_2 give a parameterization of the target fractional area which is "presented to" the warhead fragments. Since the target is not roll-symmetric, we must also describe the target "roll" with respect to the fragments. Toward this end, we treat $\mathcal{V}$ as the direction of a "central" fragment headed directly toward the target's intersection with the burst plane. The "roll" we desire is the angle between $\mathcal{V}$ and K_T. Thus roll is zero when the fragment comes straight up "under" the target. Roll is computed from:

$$\mathcal{V}' = \mathcal{V} - (\mathcal{V} \cdot I_T)I_T, \tag{32}$$

$$\mathcal{V}'' = \mathcal{V}' / \|\mathcal{V}'\| . \tag{33}$$

Thus $\mathcal{V}''$ is a unit vector in the direction of $\mathcal{V}$ with its I_T component removed (in the target J_T-K_T plane). If $\mathcal{V}'=0$, define the roll to be zero. Then, if $\mathcal{V}' \neq 0$, roll is given by:

$$\phi = \cos^{-1} (\mathcal{V}'' \cdot K_T). \tag{34}$$

Other combinations of geometric factors were tried, including definitions based upon the perpendicular vector from the target to the burst plane, and other angles besides ε_1 and ε_2, but the combination finally selected was:

$$\mathcal{V}_R,\ d,\ q,\ \eta_1,\ \eta_2,\ \phi.$$

Table A3.1, SHAZAM Coordinate Systems

System V = Target Velocity System

I_V = Target Velocity Direction

K_V = Target Zenith (Top)

$J_V = K_V \times I_V$ (Port side if no yaw or roll.)

I_V-J_V plane = Horizon Plane

System T = Target Vehicle System

I_T = Target Centerline (Forward Direction)

J_T = Target Port Side

K_T = Target Top (Vehicle Zenith)

System R = Relative System

Obtained from System V by yaw or ψ_R, and pitch or θ_R, no roll.

I_R = Direction of Missile Relative Velocity (WRT target)

System I = Inteceptor Velocity System

Obtained from System V by yaw of ψ_I, pitch of θ_I, to bring the intermediate I_{VI} to the missile velocity direction, followed by a roll about I_{VI} to bring K_I into the plane of the target velocity and missile velocity.

System M = Missile System

Obtained from System I by an elevation of θ_M to bring I_M to lie along the missile centerline (forward direction). ψ_M and ϕ_M are assumed to be zero.

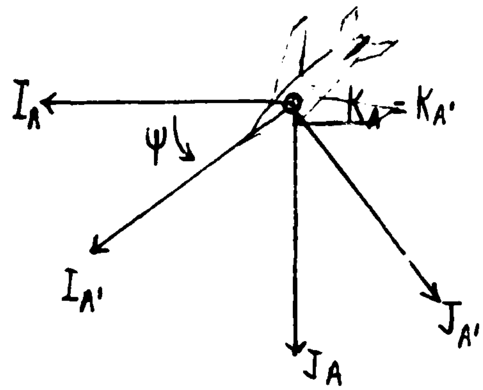


Figure A3.1
Yaw about K_A

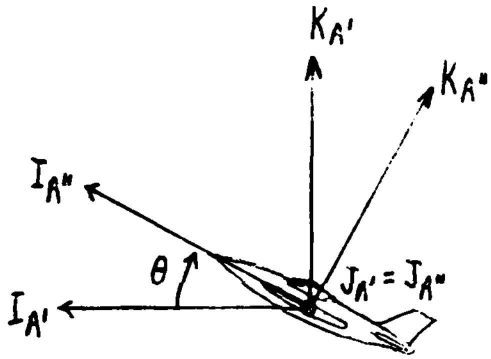


Figure A3.2
Pitch about $-J_{A'}$

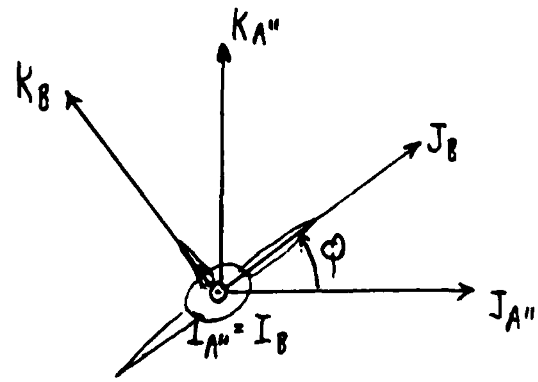


Figure A3.3
Roll about $I_{A''}$

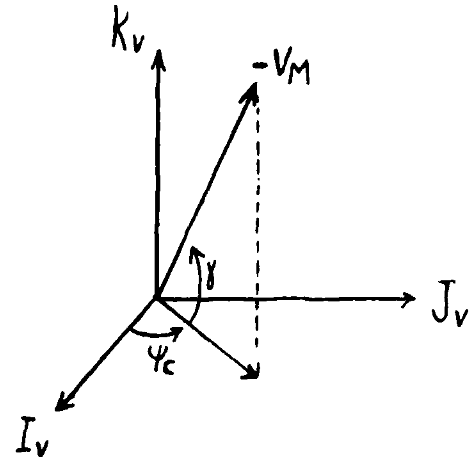


Figure A3.4
Definition of ψ_c and γ.

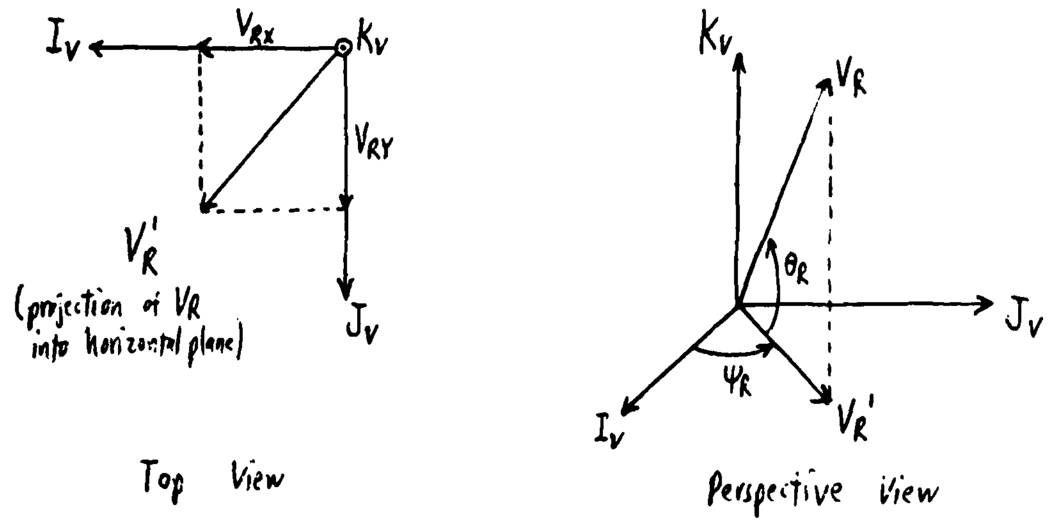


Figure A3.5
Determination of V_R

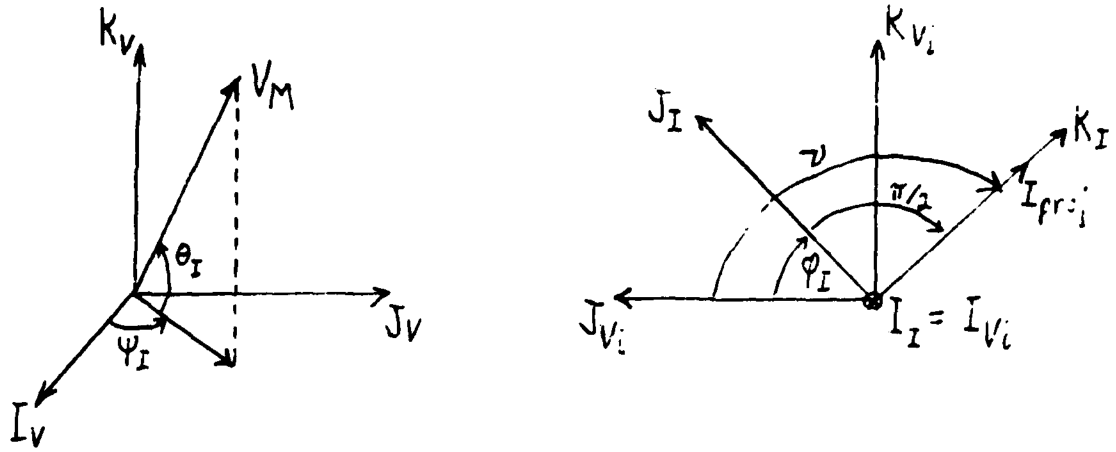


Figure A3.6

Definition of System I

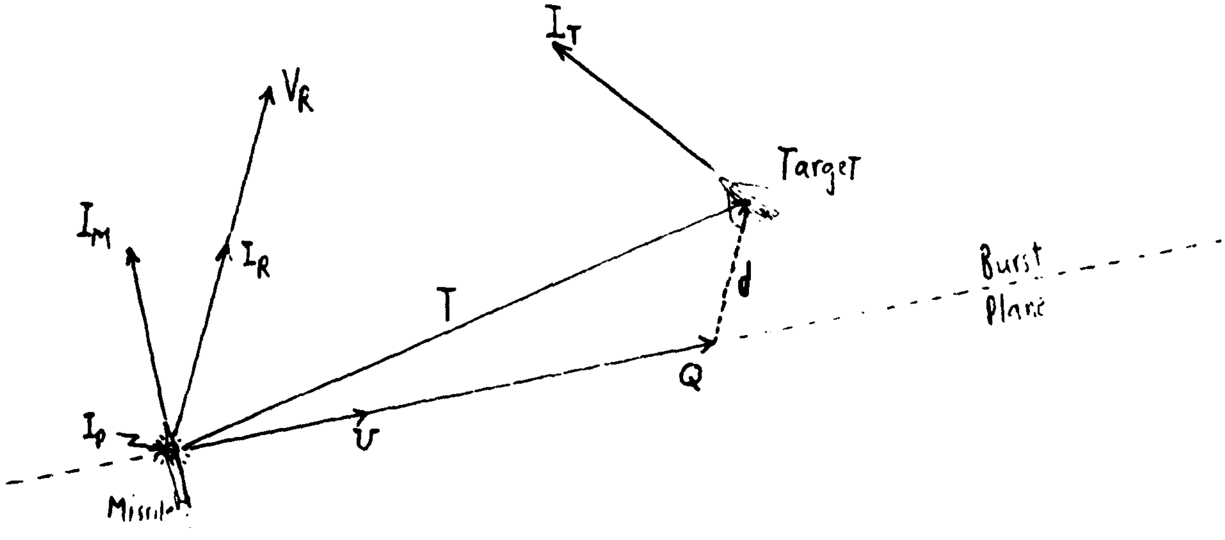


Figure A3.7
Burst Plane Geometry

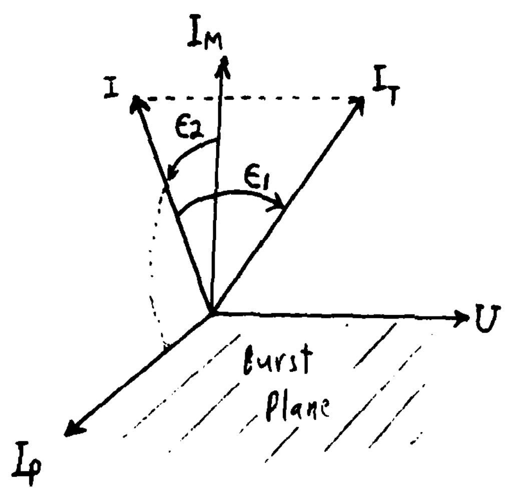


Figure A3.8
Target Attitude Angles

Appendix 4. The Surface Fitting Function

After consideration of the curve fits of Appendix 1, it was decided to utilize the full least squares method, allowing the exponent and constant multiplier to vary. The fundamental factors were to be the independent variables, along with the combinations:

$$t = d / \upsilon_R$$
$$10 / q$$
$$C_1 = \eta_1 \eta_2$$
$$(1 - \eta_1^2)^{0.5}$$
$$(1 - \eta_2^2)^{0.5}$$

Here t is the time it takes for the target center to intersect the burst plane, 10/q was introduced since the maximum pulse height falls off with increasing q, C_1 is the component of the target direction (I_T) perpendicular to the burst plane and $(1 - \eta_1^2)^{0.5}$ and $(1 - \eta_2^2)^{0.5}$ are the absolute values of the sines of ε_1 and ε_2 respectively. The last three variables were introduced since the effects of the target attitude on P_k seemed the most unpredictable. and clearly periodic. Thus the fitting function is

$$P_k = Ce^{-\left|\frac{A}{B}\right|^D}, \tag{1}$$

where A, B, C, and D are full quadratics in the fundamental factors plus the above combinations.

A full quadratic in N variables has one constant term, N linear terms, N squared terms, and N(N-1)/2 cross product terms, for a total of (N+1)(N+2)/2 terms. Thus there are 78 "independent variables", X_1 through X_{78}, and 78 coefficients of these variables to evaluate for each of A, B, C, D. Thus

$$\begin{aligned} A &= \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_{78} X_{78}, \\ B &= \alpha_{79} X_1 + \alpha_{80} X_2 + \cdots + \alpha_{156} X_{78}, \\ C &= \alpha_{157} X_1 + \alpha_{158} X_2 + \cdots + \alpha_{234} X_{78}, \\ D &= \alpha_{235} X_1 + \alpha_{236} X_2 + \cdots + \alpha_{312} X_{78}. \end{aligned} \tag{2}$$

See Table A4.1 for a summary of the variables X_j, which have been "normalized" to make the values of interest be on the order of magnitude

of 1. Note that X_{10} is the same as X_{44}, but both were kept, for simplicity. However, X_{44} was not introduced in the final fits.

The fits were accomplished by forming the "error function"

$$E = \sum_{\substack{\text{all data}\\ \text{points}}} (P_k\text{-computer} - P_k\text{-given})^2, \qquad (3)$$

and minimizing E as a function of the 312 α's.

The error function was minimized using the gradient method of Appendix 2, starting with only a few non-zero coefficients. Only the gradient component producing the largest decrease in E was used at each step, for the first 40 or 50 iterations. This allowed a total of about 40 non-zero coefficients to be introduced. Then all but these non-zero α's were fixed, and all gradient components which actually lead to a decrease in E were used. Another hundred iterations were performed in this mode.

It was found that practically any starting point would lead to fairly fast convergence to a locally optimum fit, but that some of these were much better than others. Thus the selection of starting values is critical. A subroutine, FISH, was included in the fitting program. This routine tried various combinations of starting values deemed reasonable and selected the best. The initial non-zero α's selected were as follows:

$$\alpha_3 = 8.0$$

$$\alpha_{15} = -4.5$$

$$\alpha_{79} = 1.5$$

$$\alpha_{157} = 0.5$$

$$\alpha_{165} = 0.5$$

$$\alpha_{235} = 4.0$$

To determine this set of non-zero values, the following rationale was used. Various contour plots of P_k vs. d and q, and similar variables, indicated a pulse center nearly at the point where the fragments and target arrived at the point Q (of Appendix 3) at the same time. That is

$$\Delta t = \frac{d}{v_R} - \frac{q}{v_P} = 0, \qquad (4)$$

where $\mathcal{V}_p$ is the particle flyout velocity. $\mathcal{V}_p$=5500 fps was used. Equation (4) translates approximately to

$$8X_3 - 4.5\ X_{15} = 0 \tag{5}$$

But the center of the pulse occurs where A=0. Thus to have A=0 when X_3 and X_5 satisfy (5), we choose α_3=8 and α_{15}=-4.5. Since the Keethler curve fits usually had B about equal to 5 to 7 feet, we chose a constant B which corresponded to the value of 6 for the Keethler fits, considering our various normalizations. Thus α_{79}=1.5, is the constant (only) term for B. Keethler used a constant C=1, but our data indicated a falling off with increase in q. Thus we tried

$$C = \frac{1}{2} + \frac{5}{q}, \tag{6}$$

corresponding to α_{157}=0.5=α_{165}. For D, Keethler used the constant 6. We tried the constants 2, 4, 6, 8, obtaining the best results with D=4. Thus α_{235}=4.

It was also suggested that the exponential function might not be necessary. Thus we also set A=0, thus fitting

$$P_k = C, \tag{7}$$

a simple quadratic polynomial (clipped at 0 and 1 of course). The fits obtained were not as good as the exponential fits, but little experimentation was done along these lines, and few iterations were used. A higher order polynomial, different fundamental factors, or a rational function:

$$P_k = A/B, \tag{8}$$

might lead to good fits which allow simpler (faster) computation.

Table A4.1. Variables for Quadratic Fits

$X_1 = 1$	$X_{27} = X_3 X_6$	$X_{53} = X_6 X_8$
$X_2 = \upsilon_R/3000$	$X_{28} = X_3 X_7$	$X_{54} = X_6 X_9$
$X_3 = d/50$	$X_{29} = X_3 X_8$	$X_{55} = X_6 X_{10}$
$X_4 = q/50$	$X_{30} = X_3 X_9$	$X_{56} = X_6 X_{11}$
$X_5 = \eta_1$	$X_{31} = X_3 X_{10}$	$X_{57} = X_6 X_{12}$
$X_6 = \eta_2$	$X_{32} = X_3 X_{11}$	$X_{58} = X_7^2$
$X_7 = \phi/180$	$X_{33} = X_3 X_{12}$	$X_{59} = X_7 X_8$
$X_8 = t = d/\ _R$	$X_{34} = X_4^2$	$X_{60} = X_7 X_9$
$X_9 = 10/q$	$X_{35} = X_4 X_5$	$X_{61} = X_7 X_{10}$
$X_{10} = C_1 = \eta_1 \eta_2$	$X_{36} = X_4 X_6$	$X_{62} = X_7 X_{11}$
$X_{11} = (1 - \eta_1^2)^{0.5}$	$X_{37} = X_4 X_7$	$X_{63} = X_7 X_{12}$
$X_{12} = (1 - \eta_2^2)^{0.5}$	$X_{38} = X_4 X_8$	$X_{64} = X_8^2$
$X_{13} = X_2^2$	$X_{39} = X_4 X_9$	$X_{65} = X_8 X_9$
$X_{14} = X_2 X_3$	$X_{40} = X_4 X_{10}$	$X_{66} = X_8 X_{10}$
$X_{15} = X_2 X_4$	$X_{41} = X_4 X_{11}$	$X_{67} = X_8 X_{11}$
$X_{16} = X_2 X_5$	$X_{42} = X_4 X_{12}$	$X_{68} = X_8 X_{12}$
$X_{17} = X_2 X_6$	$X_{43} = X_5^2$	$X_{69} = X_9^2$
$X_{18} = X_2 X_7$	$X_{44} = X_5 X_6$	$X_{70} = X_9 X_{10}$
$X_{19} = X_2 X_8$	$X_{45} = X_5 X_7$	$X_{71} = X_9 X_{11}$
$X_{20} = X_2 X_9$	$X_{46} = X_5 X_8$	$X_{72} = X_9 X_{12}$
$X_{21} = X_2 X_{10}$	$X_{47} = X_5 X_9$	$X_{73} = X_{10}^2$
$X_{22} = X_2 X_{11}$	$X_{48} = X_5 X_{10}$	$X_{74} = X_{10} X_{11}$
$X_{23} = X_2 X_{12}$	$X_{49} = X_5 X_{11}$	$X_{75} = X_{10} X_{12}$
$X_{24} = X_3^2$	$X_{50} = X_5 X_{12}$	$X_{76} = X_{11}^2$
$X_{25} = X_3 X_4$	$X_{51} = X_6^2$	$X_{77} = X_{11} X_{12}$
$X_{26} = X_3 X_5$	$X_{52} = X_6 X_7$	$X_{78} = X_{12}^2$

Appendix 5. Computer Programs

In order to carry out the program outlined in Appendices 1 through 4, a series of computer programs were written. Programs to carry out the pulse fitting methods of Appendix 1 were used to test the various methods only, and were not kept. All other programs were saved in permanent files in the Eglin Timesharing System. The programs were written in FORTRAN IV. These programs are:

- SBGEOM - Data Generator
- SBFIT - Fitting Program
- SBSPEED - Convergence Accelerator
- SBINTEG - 109-Cell Integration Program

The data generator program, SBGEOM, reads a file of data furnished by G. A. Keethler, converts the Keethler parameters to SHAZAM variables, transforms these to the fundamental factors, forms the 78 X_j's from these, and creates a file of X_j-values together with the associated values of Pk. This FORTRAN source program resides on the file SBGEOM, ID = K4, SN = USET1.

The fitting program uses the output of SBGEOM to fit a surface, that is the 312 α's, by using the gradient method to minimize the error function. The alphas are written onto a file which can be used as input for later runs to reduce the error even further. The source program is found in the file SBFIT, ID=KZ,SN=USET2.

The convergence accelerator uses Aitken's Δ^2 method on each component of the α-vectors to produce a new file of α's exactly like that produced by SBFIT. This new file may then be input to SBFIT for further iterations, or at least to check the new error. This program was originally written to take any odd number of sets of alphas, and extrapolate to the limit, but in the interests of saving file space, only the last three sets of alphas are output by SBFIT, and a single set is produced by SBFIT by a single application of the Δ^2 method. The source program has been saved in the file SBSPEED, ID=KZ,SN=USET2.

In the SHAZAM program, the variables Y_M and Z_M are randomized, rather than predetermined. An integration of their joint normal density function is approximated by Monte Carlo methods. G. A. Keethler used their polar coordinates, R_M and θ, and approximated the integration

of their resulting Rayleigh distribution by the "109-Cell Model". The program SBINTEG uses sample data provided by Keethler and performs the same 109-Cell Model calculations, using the P_k function of Equation A4.1, as determined by the alpha set generated by SBFIT. The source program is in the file SBINTEG, ID=KZ,SN-USET2.

A summary of these programs, and their associated subroutines and files appears in Table A5.1.

Table A5.1 - Computer Programs and Files

SBGEOM (ID=K4, SN=USET1)

DATGEN - Main program - Performs initialization and drives suuroutines

SETRIG - Initializes trigonometric constants

GETGK - Reads data from the Keethler file (tape 1)

GK2SHZ - Converts G. A. Keethler data to SHAZAM variables

SHZ2FF - Converts SHAZAM variables to fundamental factors

TRGEN - Generates rotation matrices for SHZ2FF

TRANSF - Transforms vectors by rotation matrices

TRNSPZ - Transposes (inverts) rotation matrices

MATMUL - Multiples (composes) two rotation matrices

DOT (FUNCTION) - Dot product of 3-vectors

OUT - Writes X_j's, together with Pk's on tape 2, also prints the Keethler inputs and the X_j's on the output file (tape 6)

SIZE (FUNCTION) - Norm of a vector

FF2X - Generates the 78 X_j's from the fundamental factors

Files: Input = Tape 1 - TRDATA, ID=I5, SN=USET2 (Keethler data)
Output = Tape 2 - SBDATA, ID=KZ, SN=USET2 (X_j's - Pk's)
Tape 6 - printed

SBFIT (ID=KZ, SN=USET2)

FITS - Main Program - Reads data, parameters, drives subroutines, prints final error and alphas

FISH - Fishes for good starting values for alphas

STEEP - Steepest descent (gradient method) error minimization

CHECK - Computes errors for a given set of alphas

Files: Input = Tape 1 - SBDATA, ID=KZ, SN=USET2 (From SBGEOM)
Tape 2 - SBALPHA, ID=KZ, SN=USET2 (From prior runs)
Tape 5 - input (system) (control parameters)
Output = Tape 3 - SBALPHA, ID=KZ, SN=USET2 (new α'a)
Tape 6 - printed

SBSPEED (ID=KZ, SN=USET2)

SPEED - Main Program - Reads α-sets, generates one new α-set

Files: Input = Tape 1 - SBALPHA, ID=KZ, SN=USET2 (from SBFIT)
Output = Tape 2 - SBALPHA, ID=KZ, SN=USET2 (new version)
Tape 6 - printed

SBINTEG (ID=KZ, SN=USET2)

INTEG - Main Program - Initializes, reads data files, drives subroutines, does 109-cell model

SETRIG - Initializes trigonometric constants

GK2SHZ - Converts G. A. Keethler data to SHAZAM variables

SHZ2FF - Converts SHAZAM variables to fundamental factors

TRGEN - Generates rotation matrices

TRANSF - Transforms vectors by rotation matrices

TRNSPZ - Transposes rotation matrices

MATMUL - Multiples two rotation matrices

DOT (FUNCTION) - Dot product

SIZE (FUNCTION) - Norm of a vector

FF2X - Generates the 78 X_j's from the fundamental factors

PKFUN (FUNCTION) - The fit function for the P_k's, utilizing the α's from SBFIT

Files: Input = Tape 1 - SIGMA, ID=I5, SN=USET2 (trial points)
Tape 2 - M109, ID=I5, SN=USET2 (109 cell points)
Tape 3 - SBALPHA, ID=KZ, SN=USET2 (from SBFIT)
Tape 5 - Input (system), (control parameters)
Output = Tape 6 - printed

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FINAL REPORT

PARAMETERIZING BOUNDARY-LAYER PROCESSES FOR GENERAL CIRCULATION MODELS

Prepared by:	Dr. Stephen Berman
Academic Rank:	Associate Professor
Department and University:	Earth Science Department State University of New York, College at Oneonta

Research Location:	Air Force Geophysics Laboratory, Meteorology Division Climatology and Dynamics Branch
USAF Research Colleague:	Dr. Chien-hsiung Yang
Date:	August 12, 1980
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PARAMETERIZING BOUNDARY-LAYER PROCESSES FOR GENERAL CIRCULATION MODELS

by

Dr. Stephen Berman

ABSTRACT

The principal ways of parameterizing boundary-layer momentum, heat, and moisture fluxes for inclusion in general circulation models (GCM's) are presented. Those for the surface layer include the Bulk-Transfer, Monin-Obukhov Similarity, and PBL-Matching techniques. Those for the Ekman layer include K-Theory and Surface-Layer Extrapolation techniques. A comparison of boundary-layer parameterization used in six diferent operational GCM's is provided in table form, followed by preliminary evaluations of the schemes taken from published reports. It is recommended that the methods be tested in systematic fashion by incorporating them into a specific GCM, one at a time, with verification made with observed data.

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I. INTRODUCTION

With plans to develop its own operational, moist, spectral, general circulation model (GCM) in the next few years, the Climatology and Dynamics Branch at the Air Force Geophysics Laboratory invited me to spend the summer of 1980 with them to study how best to formulate boundary-layer (BL) processes for such a model.

The need to include BL processes in GCM's stems directly from the governing physical equations. In Cartesian Coordinates these may be written

Horizontal Momentum: $$\frac{\partial \vec{V}}{\partial t} + \vec{V}\cdot\nabla\vec{V} + w\frac{\partial \vec{V}}{\partial z} + 2\vec{\Omega}\times\vec{V} + \frac{1}{\rho}\nabla P = \vec{F} \tag{1}$$

Thermodynamic: $$\frac{\partial \theta}{\partial t} + \vec{V}\cdot\nabla\theta + w\frac{\partial \theta}{\partial z} = Q \tag{2}$$

Moisture Continuity: $$\frac{\partial q}{\partial t} + \vec{V}\cdot\nabla q + w\frac{\partial q}{\partial z} = M \tag{3}$$

Mass Continuity: $$\frac{\partial \rho}{\partial t} + \nabla\cdot\rho\vec{V} + \frac{\partial}{\partial z}(\rho w) = 0 \tag{4}$$

which contain the meteorological variables $\vec{V}$ (horizontal wind vector), w (vertical velocity), θ (potential temperature), P (pressure), q (specific humidity), and ρ (density), and where $\vec{F}$, Q, and M represent sources and sinks of horizontal momentum (friction), heat, and moisture, respectively. The 4 prognostic equations above are supplemented by 4 diagnostic equations needed to close the system. These are the Equation of State, Hydrostatic Equation, Poisson's Equation, and the Virtual Temperature Equation.

Equations (1)-(3) are relatively easy to solve for the special case of inviscid ($\vec{F}$=o), adiabatic (Q=o), unsaturated (M=o) flow. For this case the right sides of the equations all vanish. Although the assumptions are reasonably

valid in the upper levels of the troposphere for short time periods, they become invalid over longer times, especially in the lower troposphere. Here frictional effects, phase changes of water, convection, and radiation are significant and cannot be ignored. Though small in size, these subgrid-scale processes interact in nonlinear ways with larger scales of motion. Some examples of this interaction are the frictional convergence leading to cross-isobaric flow into surface lows and the rapid intensification of continental air masses as they pass over warm oceans. The exchange between the planetary boundary layer (PBL) and the overlying free atmosphere takes place through large-scale vertical motions at the top of the PBL.

The term parameterization is used to describe the technique of relating smaller, subgrid-scale processes to larger, grid-resolvable variables. The object of parameterization is to express $\vec{F}$, Q, and M, all microscale and mesoscale processes in terms of synoptic-scale measurements of $\vec{V}$, θ, P, q, and ρ. Table 1 below shows the principal sources and sinks of $\vec{F}$, Q, and M and the layers of the atmosphere where they predominate.

Table 1. Sources and Sinks of Friction, Heat, and Moisture in the Atmosphere

Atmospheric Layer	Friction	Heat	Moisture
Ground Level (< 1 cm)	molecular viscosity	molecular heat conduction; surface radiation	molecular diffusion
PBL (1cm - 1 km)	turbulent momentum flux-vertical component	turbulent sensible and latent heat fluxes-vertical components	turbulent moisture flux-vertical component
Free Atmosphere (> 1 km)	intermittent turbulent momentum fluxes in clouds, jets	cumulus convection; cloud radiation; latent heat release	condensation and precipitation

Although present everywhere in the atmosphere, molecular processes are only effective very close to the lower boundary. Vertical turbulent fluxes tend to dominate the PBL, the lateral components being negligibly small (except perhaps over highly inhomogeneous terrain). A variety of sources and sinks occur in the free atmosphere, mainly in connection with clouds. This study concentrates on parameterizing the vertical turbulent fluxes in the PBL.

A few words about the PBL are in order. The PBL consists of a lower "surface layer" from 5-100m thick in which it is assumed that all vertical turbulent fluxes remain constant with height. The fluxes really decrease in magnitude by as much as 20%, but this variation is ignored. Wind direction turning with height is likewise ignored. Above the surface layer lies the well-mixed "Ekman layer" of variable thickness, but usually less than 2 km, where turbulent fluxes decrease rapidly with height, and the wind turns significantly, approaching geostrophic balance at the top of the layer. PBL thickness is not constant but varies in time and space depending on many factors including surface heat and moisture fluxes, lapse rates, advection, and entrainment of turbulent air near the top of the PBL. Typically, its depth varies from a few tens of meters at night to 2 km during sunny afternoons. Around sunset the PBL collapses to a shallow layer until daytime heating renews the cycle.

II. OBJECTIVES OF THE RESEARCH EFFORT

The main goals of this research study are to:

(a) review recent meteorological literature for appropriate techniques to parameterize the vertical turbulent fluxes of momentum, heat, and moisture in the PBL,

(b) summarize PBL parameterization schemes employed in six different operational GCM's (GFDL, NCAR, NMC, UCLA, GISS, and ECMWF models),

(c) evaluate the strengths and weaknesses of the different schemes, and

(d) recommend a course of action for selecting the most effective parameterization technique.

III. SURFACE-LAYER FLUXES

In GCM's having such coarse resolution that the whole PBL is placed below the lowest internal grid level, only surface-layer fluxes need be parameterized. In models having enough resolution to place several grid levels in the lowest 3 km, we must parameterize both the surface layer and the Ekman layer. Once the surface layer fluxes have been parameterized, it is easy to extrapolate them upward into the Ekman layer[1].

After separating the variables in Eqs. (1-3) into mean (overbars) and fluctuating (primes) components, applying Reynolds' rules of averaging to the Navier-Stokes formulations for the stresses, assuming incompressible flow and horizontal homogeneity, we can express the vertical component of the turbulent frictional stress as

$$\vec{F} = \frac{1}{\rho}\frac{\partial \vec{\tau}}{\partial z} \quad \text{where } |\vec{\tau}| = \left(\tau_x^2 + \tau_y^2\right)^{\frac{1}{2}} \quad \text{and } \tau_x \equiv -\rho\overline{u'w'}, \ \tau_y \equiv -\rho\overline{v'w'} \tag{5}$$

The results for Q and M are similar:

$$Q = \frac{1}{\rho c_p}\frac{\partial H}{\partial z}, \quad \text{where } H \equiv -\rho c_p \overline{w'\theta'} \tag{6}$$

$$M = \frac{1}{\rho}\frac{\partial E}{\partial z}, \quad \text{where } E \equiv -\rho\overline{w'q'} \tag{7}$$

We now examine 3 ways of parameterizing $\vec{\tau}$, H, and E for the surface layer:

(a) Bu.k-Transfer Method

The expressions for the fluxes in the Bulk-Transfer method are:

$$|\vec{\tau}_s| = \rho C_D \bar{u}_r^2 \tag{8}$$

$$H_s = -\rho c_p C_H \bar{u}_r (\bar{\theta}_r - \bar{\theta}_o) \tag{9}$$

$$E_s = -\rho C_E \bar{u}_r (\bar{q}_r - \bar{q}_o) \tag{10}$$

where subscript "s" refers to the surface layer, "r" refers to a reference level in the surface layer (e.g., anemometer height), and "o" refers to ground level. U_r is the mean wind at level "r" and defines the direction of the X-axis. If the GCM lacks an internal grid level in the surface layer, U_r, θ_r, and q_r will have to be extrapolated downward from the lowest available grid level. This may lead to large errors if the lowest available grid level is far above the PBL. Ground-level values $\bar{\theta}_o$ and $\bar{q}_o$ are also needed. These must be prescribed diagnostically, or forecast via energy and moisture balance equations for the lower boundary. The dimensionless drag coefficients C_D, C_H, and C_E themselves need to be parameterized. They are often assumed equal and assigned fixed values. Sometimes a single value is used planetwide; sometimes different values are assigned to land and ocean surfaces. A method of estimating C_D from terrain features was formulated by Cressman[2] and is often used. The main drawback with these simple drag-coefficient parameterizations is that they usually ignore stability, baroclinicity, and local surface roughness effects. It is known that the drag coefficients can vary several orders of magnitude at the same location under different meteorological

conditions. A better estimation of drag coefficients based on Monin-Obukhov Similarity Theory is available, but requires knowing Z_o (surface roughness length) and L (Obukhov length). We discuss this method next.

(b) Monin-Obukhov Similarity Theory

Well-established surface-layer flux-profile relations have been developed in the past decade from measurements over homogeneous terrain[3]. When combined with Monin-Obukhov similarity theory, these yield explicit expressions for drag coefficients which incorporate stability and surface roughness effects.

Monin-Obukhov similarity theory for the surface layer adopts a scaling velocity (u_*), a scaling temperature (θ_*), a scaling specific humidity (q_*), and a scaling length (L, the Obukhov length) - all assumed invariant. When applied to the mean gradients of $\bar{U}$, $\bar{\theta}$, and $\bar{q}$ we get:

$$\frac{kz}{u_*}\frac{\partial \bar{u}}{\partial z} = \phi_m\left(\frac{z}{L}\right), \quad \text{where} \quad u_* \equiv \left(\frac{\tau_s}{\rho}\right)^{\frac{1}{2}} \tag{11}$$

$$\frac{kz}{\theta_*}\frac{\partial \bar{\theta}}{\partial z} = \phi_H\left(\frac{z}{L}\right), \quad \text{where} \quad \theta_* \equiv \frac{H_s}{\rho c_p u_*} \tag{12}$$

$$\frac{kz}{q_*}\frac{\partial \bar{q}}{\partial z} = \phi_E\left(\frac{z}{L}\right), \quad \text{where} \quad q_* \equiv \frac{E_s}{\rho u_*} \tag{13}$$

where k = von Karman's constant ≈ 0.4.

Integrating Eqs. (11), we find:

$$\frac{\bar{u}_r}{u_*} = \int_{z_o}^{z_r} (kz)^{-1}\phi_m\left(\frac{z}{L}\right) dz \equiv F_m\left(\frac{z_r}{z_o}, \frac{z_r}{L}\right) \tag{14}$$

where Z_r is the height of reference level r (in surface layer). Similar integrations of (12) & (13) yield:

$$\frac{\bar{\theta}_r - \bar{\theta}_o}{\theta_*} \equiv F_H\left(\frac{Z_r}{Z_o}, \frac{Z_r}{L}\right) \tag{15}$$

and,

$$\frac{\bar{q}_r - \bar{q}_o}{q_*} \equiv F_E\left(\frac{Z_r}{Z_o}, \frac{Z_r}{L}\right) \tag{16}$$

When Eqs. (8)-(10) are combined with Eqs. (14-16), we find

$$C_D = (F_M)^{-2}, \quad C_H = (F_M F_H)^{-1}, \quad C_E = (F_M F_E)^{-1} \tag{17}$$

Empirical expressions for F_M and F_H are available as functions of Z_r/Z_o and Z_r/L.[1,4] Z_r/L can be estimated by means of an iterative scheme using the Bulk Richardson Number, Ri_b:

$$Ri_b = \frac{g Z_r (\bar{\theta}_{vr} - \bar{\theta}_o)}{\bar{\theta}_{vo} \bar{U}_r} \tag{18a}$$

where subscript "v" denotes the virtual potential temperature. Another expression for Ri_b is available by combining Eq. (18) with Eqs. (15) & (16) and by assuming $F_H = F_E$:

$$Ri_b = \frac{1}{k} \frac{F_H}{F_m^2} \frac{Z_r}{L} \tag{18b}$$

The procedure used to compute the drag coefficients is:

1. Compute Ri_b <u>via</u> Eq. (18a).
2. Guess an initial value for Z_r/L and use it to compute initial estimates of F_H and F_M from published algorithms.[1,4]
3. Use Eq. (18b) to compute an estimate of Ri_b.
4. Compute Ri_b (18a) - Ri_b (18b) = ε.
5. Minimize ε by systematically trying new values for Z_r/L.
6. Repeat steps 2 through 6.
7. When ε is sufficiently small, use the final values of F_M and F_H to compute the drag coefficients <u>via</u> Eq. (17).

Under conditions of extreme instability ($Z_r/L \leq -3$), the drag coefficients should be replaced by expressions involving the height of the PBL (h) and the convective velocity (V_c). These "free convection" expressions are given by Benoit.[5]

It remains to parameterize Z_o for use with this method. Unfortunately, this is still an unresolved problem. Kung[6] derived the following regression relationship based on area-weighting values of log Z_o over a large region of various vegetation types:

$$\log Z_o = 1.19 \log h_o - 1.24 \tag{19}$$

where h_o is the mean height of the roughness elements in centimeters. "The ratio h_o/Z_o varies from about 4.5 for forest trees to about 27 for sand, indicating a five-fold range in the values of log Z_o .... Therefore, the assumption of a single value of Z_o for all land areas, often made in GCM's, would hardly seem justified."[1] Over the oceans, Charnock has suggested the expression

$$z_o = b u_*^2 / g \tag{20}$$

where g is gravity and b is an empirical constant, usually between 0.01 and 0.1, the actual value depending on the wind fetch and duration. It is to be emphasized that these formulas are tentative with the exact nature of the roles of micro-, meso-, and large-scale topographic features on producing an "effective" roughness length still a matter for conjecture.[1]

(c) PBL Matching Theories

In GCM's providing ground-level values of θ_o and q_o, but lacking information on reference-level variables U_r, θ_r, and q_r, surface fluxes can be parameterized in terms of mean values at a height comparable to the top of the PBL, h, or from their layer-averaged values. The parameterizations are derived by connecting, or "matching," mean profiles predicted by surface-layer theory with those predicted for the Ekman layer.

Analogous to Eqs. (14)-(16) we can write

$$\frac{\bar{u}_m}{u_*} = F_m'\left(\frac{h}{z_o}, \frac{h}{L}\right) \tag{21}$$

$$\frac{\bar{\theta}_m - \bar{\theta}_o}{\theta_*} = F_H'\left(\frac{h}{z_o}, \frac{h}{L}\right) \tag{22}$$

$$\frac{\overline{q}_m - \overline{q}_o}{q_*} = F_E'\left(\frac{h}{z_o}, \frac{h}{L}\right) \tag{23}$$

where the subscript "m" refers to layer-averages, and F_M', F_H', F_E' are the counterparts of F_M, F_H, F_E. Deardorff[7] provides empirical formulas for F_M', F_H', and F_E' based on his numerical model studies. Using the Bulk Richardson Number expressions given earlier (Eqs. 18a & 18b) but with subscript "m" replacing "r" and with "h" replacing "Z," we follow the same seven steps outlined in Part (b) to determine the final values of F_M', F_H', and F_E' and afterwards, the drag coefficients.

The additional variable needed for this method is the height of the PBL, h. Dimensional arguments have suggested $h = \frac{u_*}{f}$ or $h = \left(\frac{Lu_*}{f}\right)^{\frac{1}{2}}$, though these cannot be used near the equator or under neutral stability ($|L| \to \infty$). For the neutral and stable cases, Deardorff suggests using

$$h - Z_S = \left(\frac{1}{30L} + \frac{f}{.35u_*} + \frac{1}{Z_{TROP}}\right) \tag{24}$$

where Z_S=height of the surface, and Z_{trop}=height of the tropopause. The singular cases of f=o and $|L| \to \infty$ cause no problems in Eq. (24). For the unstable case, Deardorff proposes using a time-dependent (prognostic) expression for h:

$$\frac{\partial h}{\partial t} = \overline{W}_h - \vec{\overline{V}}_h \cdot \nabla \overline{h} + S + \nabla \cdot \left(K \nabla \overline{h}\right) \tag{25}$$

where $\overline{W}_h$ is the vertical velocity at height h obtained from the GCM, $\vec{\overline{V}}_h \cdot \nabla \overline{h}$ is the horizontal advection of PBL height, S is the source term which involves penetrative convection by cumulus clouds and subsequent entrainment of stable air above into the PBL,

and K is an eddy-diffusion coefficient representing <u>lateral</u> diffusion of $\bar{h}$. In practice one can use the layer-averaged winds $\bar{V}_m$ in place of $\bar{V}_h$ because of thorough vertical mixing under unstable conditions.

Equation (25) presents a formidable challenge to solve completely, since it implies parameterizing cumulus convection, assumes the horizontal distribution of $\bar{h}$ is known, and requires a parameterization for K. The reader is referred to Deardorff[7] for additional details. We leave the surface layer at this point and examine the Ekman layer next.

IV. EKMAN-LAYER FLUXES

For GCM's with fine resolution in the vertical, it will be necessary to parameterize the turbulent fluxes above the surface layer. There are two principal techniques used: K-theory and surface-layer extrapolation.

(a) K-Theory

By analogy with molecular processes, we set the fluxes proportional to the gradients of mean quantities:

$$\vec{\tau} = \rho K_m \frac{\partial \vec{\bar{V}}}{\partial z} \tag{26}$$

$$Q = -\rho c_p K_H \left(\frac{\partial \bar{\theta}}{\partial z} - \gamma_{cg} \right) \tag{27}$$

$$E = -\rho K_E \frac{\partial \bar{q}}{\partial z} \tag{28}$$

where γ_{cg} is a countergradient flux and K_M, K_H, and K_E are the eddy diffusion coefficients for momentum, heat, and moisture, respectively. By finite differencing in the vertical, the derivatives can be approximated if the GCM can provide mean variables at two levels in the Ekman layer. The difficulty lies with the

specification of the K's. Like the drag coefficients in surface-layer formulations, the K's vary with height, stability, roughness, and baroclinicity. Many K-distributions (see, for example, Table 8.4, in Brown[8]) have appeared in the literature. They all seem to provide satisfactory results for neutral stability in the surface layer, but fare poorly for thermally stratified conditions (unstable or stable), especially above the surface layer.

(b) SL-Extrapolation

A more reliable method, based on numerous studies, suggests that for unstable conditions simple linear profiles suffice:

$$\left.\begin{aligned} \tau_x &= \tau_s(1-\xi) \\ \tau_y &= 0 \\ H &= H_s(1-\xi) \\ E &= E_s(1-\xi) \end{aligned}\right\} \begin{array}{l} \text{for } \xi \leq -2 \\ \text{where } \xi \equiv \dfrac{z}{h} \end{array} \tag{29}$$

Under neutral and stable stratification, Deardorff's[7] empirical polynomial equations for stress fit his 3-dimensional numerical model well. They are given by

$$\begin{aligned} \tau_x &= \tau_o\left(1-2.80\xi + 2.39\xi^2 - 0.61\xi^3\right) \\ \tau_y &= \tau_o\left(1.83\xi - 2.91\xi^2 + 1.20\xi^3\right) \end{aligned} \tag{30}$$

The linear heat and moisture fluxes given for the unstable case are also suggested for neutral and stable conditions by Arya[1].

V. PARAMETERIZATION SCHEMES USED IN SEVERAL GCM's

A summary of the salient boundary-layer features for 6 operational GCM's is provided in Tables 2A and 2B, based partly on Bhumralkar's[9] comprehensive review. The 6 models are:

(1) GFDL (1971 version) - Geophysical Fluid Dynamics Laboratory, Holloway and Manabe[10],

(2) NCAR (1971 version) - National Center for Atmospheric Research, Kasahara and Washington[11], and Washington and Kasahara[12],

(3) UCLA (1972 version) - University of California, Los Angeles, Arakawa[13],

(4) GISS (1974 version) - Goddard Institute for Space Studies, Somerville et. al[14],

(5) NMC (1976 version) - National Meteorological Center, Stackpole[15], Shuman and Hovermale[16],

(6) ECMWF (1979 version)- European Centre for Medium Range Weather Forecasts, Tiedtke, et. al.

The 6 GCM's vary considerably in the number of levels assigned to the PBL. These range from none in the NCAR (1971) and UCLA (1972) models to 5 in the GFDL (1971) version. Surface-layer drag coefficients are computed several different ways, ranging from using a single worldwide constant value (NCAR, 1971) to evaluation by means of Monin-Obukhov similarity theory (ECMWF, 1979). Ground-level values of θ_o or T_o are usually obtained from surface energy balance, and q_o usually obtained from a surface hydrologic balance equation, except over the

ocean where it is set equal to its saturation value. Reference level values for U_r, T_r, q_r are most often obtained directly from a level in, or close to, the surface layer. Those models lacking PBL grid levels use the cruder approach of flux extrapolation, assuming no flux divergence. Ekman-layer fluxes are unanimously obtained from K-theory with a variety of assumptions about K. The most sophisticated model overall appears to be the ECMWF model.

Table 2A. Comparison of Surface-Layer Parameterizations for Various GCM's

Model	No. of Internal Levels, Coordinates	PBL Levels (Approx. Hts)	Surface-Layer Fluxes: Values for C_D, C_H, C_E, Z_o	Surface-Layer Fluxes: Determination of reference and ground-level variables
GFDL (1971)	9, σ	80m 520m 1.49km	$C_D=C_H=C_E$ $C_D=\left[\frac{k}{\ln\frac{Z_r}{Z_o}}\right]^2=.002$ with k=0.4, Z_r=80m, Z_o=1cm assumed (for both land and sea).	80m prognostic equations used for V_r, T_r, q_r. To: (land) estimated from surface energy balance equation with zero surface heat capacity and no surface heat conduction. To: (sea) specified from climatic means - February values used. q_o: assumed saturated at ground.
NCAR (1971)	6,Z	None; lowest level is 3 km	$C_D=C_H=.003$ $C_E=0.7\ C_D$ to reduce evaporation rate	No flux divergence assumed for the boundary layer. Reference-level drag formulas set equal to K-theory relations at 3 km. With drag coefficients and K's specified, U_r, T_r and q_r are thereby determined. To, q_o (land): are determined from surface energy and hydrologic balances. To (water): specified from climatology.

Table 2A. Comparison of Surface-Layer Parameterizations for Various GCM's - continued

Model	No. of Internal Levels, Coordinates	PBL Levels (Approx. Hts)	Surface-Layer Fluxes: Values for C_D, C_H, C_E, Z_o	Surface-Layer Fluxes: Determination of reference and ground-level variables
UCLA (1972)	3, σ	No explicit level in PBL. Lowest level is ≈ 2 km.	$C_D = C_H = C_E$ C_D formulas are provided for over open ocean land and depend on stability and roughness.	U_r extrapolated to surface-layer from 800 mb q_r, T_r computed by flux extrapolation similar to NCAR's. To: surface energy balance without ground heat conduction. Prog. eq. has nonzero sfc specific heat. q_o: hydrologic balance equation.
GISS (1974)	9, σ	600 m, 1.6 km	$C_D = C_H = C_E$ (similar to UCLA formulation)	(similar to UCLA and NCAR formulation).
NMC (1976)	8, σ	420 m	$C_D = C_H = C_E$ C_D is a function of terrain as determined by Cressman's formulation.	420m-level prognostic equations used for U_r, T_r, q_r. To (land): surface energy balance; q_o equals the saturation value over the oceans, and equals (1-A) over land, where A is the albedo.
ECMWF (1979)	15, σ	3 levels below 1 km	Monin-Obukhov similarity theory used. $Z_o = .0032 \frac{u_*^2}{g}$) over water (Charnock's formula. Z_o (land): formula used depends on terrain roughness and vegetation.	To (sea): prescribed and kept constant. To (land): surface energy balance equation solved with nonzero soil thermal capacity and including simple soil heat conduction and snow-melt. q_o (sea) = saturated value q_o (land) = surface hydrologic balance equation. U_r, q_r, T_r presumably determined from prognostic equations.

Table 2B. Comparison of Ekman-Layer Parameterizations for Various GCM's

Model	Ekman Layer Fluxes	Other Features
GFDL (1971)	K-theory $$K_m = \ell^2 \left\| \frac{\partial \vec{V}}{\partial z} \right\|$$ where ℓ increases linearly to 75 m, then decreases to a value of zero at 2.5 km ℓ = 30 m at Z = 75 m $K_H=0$ $K_E = K_m$	Non-linear lateral diffusion incorporated into governing equations. Moist convective adjustment made: when air is saturated and lapse rate is super wet-adiabatic, equiv. pot. temp. is made uniform with height and rel. humidity = 100%. GFDL (1974) version: 18 levels in vertical; lowest at 36 m.
NCAR (1971)	K-theory $K_m=K_H=K_E$ K_H is calculated from empirical formulas, which (suggested by Deardorff) include height, stability and orographic effects. See Washington and Kasahara[12]	Non-linear lateral diffusion incorporated into governing equations.
UCLA (1972)	Ekman layer not distinguishable. Surface layer fluxes at 500 m are really in the Ekman layer	No explicit horizontal diffusion of momentum, heat, or moisture.
GISS (1974)	K-theory $K_m=K_H=K_E=10^3\ cm^2s^{-1}$ (used at all layers above the first)	No explicit horizontal diffusion of momentum, heat, or moisture.

Table 2B. Comparison of Ekman-Layer Parameterizations for Various GCM's - continued

Model	Ekman Layer Fluxes	Other Features
NMC (1976)	(same as UCLA)	(same as UCLA)
ECMWF (1979)	K-theory $K_M=K_H=K_E$ K's calculated from mixing-length hypothesis as expressed in GFDL model above, but with ℓ depending on height and stability, following Blackadar's formulation.	Kuo convection scheme used for parameterization of cumulus convection. No explicit horizontal diffusion of momentum, heat, or moisture. Evaporation of convective rainfall is parameterized.

VI. EVALUATION OF BOUNDARY-LAYER PARAMETERIZATIONS

The only way to decide which BL parameterization produces the "best" results is to run a GCM with different parameterization schemes using the same initial data and verifying the model forecasts with observed data. To my knowledge the only published account of such an experiment is Cressman's[2] paper on using a terrain-dependent drag coefficient to better simulate frictional effects in mountainous regions. Other published papers compare several BL schemes with each other, but do not verify the results with observations, the ultimate test. A brief account of these papers follows.

Using a 2-level, quasi-geostrophic, barotropic model, Cressman[2] made the following tests: for a series of ten different days he made two 48-hour forecasts - one without mountain and frictional effects, and one with. Verification was based on root-mean-square errors of the observed 500 mb wind and height fields over the Rocky Mountains. His figures indicate about a 10% overall reduction in error when mountain and frictional effects were included. This improvement would probably have been more pronounced had

the surface wind been better estimated. Cressman assumed the surface wind speed was 20% of the 500 mb wind, since the model provided winds only at the 500 mb level.

Delsol, Miyakoda and Clarke[18] discuss the results of modifying the 9-layer GFDL model by successively adding 5 new boundary-layer features, namely (1) different drag coefficients for land and sea, (2) Monin-Obukhov similarity determination of drag coefficients, (3) parameterization of K_m as a function of height, wind speed, and stability, (4) diurnal variation of insolation, and (5) heat conduction into the soil. The purpose of the study was to determine the relative magnitude of each effect. No comparison with observed data was attempted. The authors conclude that varying the surface drag coefficient had the most effect; second in importance was the Ekman-layer parameterization, and third, the Monin-Obukhov treatment. The diurnal effect gave the smallest contribution tested. In total, all these effects did not produce a particularly large influence on the large-scale flow until about 7 days. The effects became sizeable after 10 days. These results prompted Pasquill (1971) to conclude that "if confirmed, much of the detail of boundary-layer effects will be unnecessary for global circulation models ...."

Arya[19], in studying the effects of inhomogeneous terrain on theoretical formulations of the neutral barotropic Ekman layer, showed that very slight horizontal gradients in friction velocity would result in significant deviations of the wind hodographs from those for the homogeneous case. He also showed in the lowest tens of meters the neutral wind profile remains approximately logarithmic regardless of surface inhomogeneity, but in the height range from 50-500m it may not bear much resemblance to any of the theoretically-derived wind spirals. Thus Arya concluded: for numerical weather prediction purposes fancy K-models may not be needed for the Ekman layer, and a simple model in which an averge constant eddy viscosity is assumed for the whole Ekman layer may be just as good.

In a more recent paper, Miyakoda and Sirutis[20] use an 18-level vertical grid (lowest level at 20m) to compare three different GCM's with varying turbulent transfer processes and cumulus convection schemes. The three GCM's are: the 1965 GFDL model, the Mellor-Yamada turbulent closure model and the 1974 UCLA model. In the Mellor-Yamada model, Monin-Obukhov similarity theory is used for the surface layer with Z_o given by Charnock's formula over the sea and Z_o=16.8 cm assumed over land. Above the surface layer the vertical sensible heat and momentum transfer is parameterized by the turbulent closure model of level 2.5. The scheme uses algorithms for K_m and K_H which include mixing length, stability, wind shear and turbulent energy. A prognostic equation for turbulent energy is solved separately. In the other two GCM's vertical heat transfer are modeled by different dry and moist convective adjustment schemes.

Thirty-day integrations were undertaken with the models starting with initial conditions on March 4, 1965. The authors conclude that the UCLA and Mellor-Yamada models ran without difficulty, producing generally realistic, though differing, rainfall distributions. The GFDL model created a large amount of cooling near the earth's surface compensated by a large degree of warming aloft due to condensation, resulting in fictitious rain or fog. Also this model produced a greater amount of tropical rain over land then over the sea. The UCLA cumulus convection scheme produced a deeper penetrative convection than the moist convective adjustments of the other two models.

VII RECOMMENDATIONS

Despite all that's been said, we have little information on how well the various parameterization schemes work in practice. Relative comparisons of one method with another are not sufficient to decide this. What we require are systematic sensitivity tests of each parameterization method incorporated one at a time into a specific GCM with fixed initial conditions. This is necessary because the complexity of the schemes and their nonlinear interactions with other parts of the model make it difficult to predict

in advance what the outcome will be. As an example of the complexity of the problem, consider how a change in the drag coefficient affects precipitation rate.[18] Increasing C_D implies greater surface roughness and hence greater frictional convergence. This may lead to the filling of surface lows and a subsequent decrease in precipitation. On the other hand, it may lead to intensified upward motion, decreased stability, and an increase in precipitation. Clearly, which occurs would depend on other factors such as large-scale convergence and divergence patterns aloft. The processes are interdependent and nonlinear. Thus, verification with actual observations is the only true test of a parameterization scheme's efficacy.

I recommend that several BL parameterization techniques be tested with the NMC-LFM, 6-layer model now being programmed at AFGL/LYD. This model is not ideal because its lowest grid level is 50 mb ($\approx$420m) above the surface, giving no detail in the surface layer. Nevertheless, it would give us valuable experience in developing appropriate verification procedures useful in future, higher-resolution, models. We could begin by testing the simplest drag-coefficient parameterization schemes: (1) C_D=constant everywhere, (2) C_D different over land and water, and (3) C_D given by Cressman's formulation. The GCM should be run with each of these parameterizations for at least 10 days, for 10 different cases. A suitable verification scheme will need to be devised. If verification results indicate a significant improvement in the forecasts as one increases the C_D complexity, the Monin-Obukhov similarity scheme should be tried next with different roughness length parameterizations. Only after such systematic experimentation will we have an objective rationale for adopting a particular parameterization method. Since it is not obvious that the conclusions of these experiments would carry over to different GCM's, the experiments would need to be repeated with AFGL's moist spectral model, when it is ready.

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FINAL REPORT

INFERENTIAL PROCESSOR

Prepared by:	Frank Markham Brown
Academic Rank:	Associate Professor
Department and University:	Department of Electrical Engineering University of Kentucky
Research Location:	Air Force Wright Aeronautical Laboratory System Avionics Division Information Processing Technology Branch Data and Signal-Processing Group
USAF Research Colleague:	Dr. Donald L. Moon
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INFERENTIAL PROCESSOR

by

Frank Markham Brown

Abstract

A new type of computer, called an inferential processor, is proposed and some of its potential applications are discussed. This machine is special-purpose in the ordinary sense; it is general-purpose, however, within the domain of propositional logic and Boolean algebra. The inferential processor is designed to function as an adjunct to a general-purpose (host) computer, performing a variety of deductive operations on logical data supplied by the host. The time required to perform tasks requiring extensive logical deduction (such as the diagnosis, on-line, of faults in complex systems) can be drastically reduced by the introduction of such a processor. The design of the processor is detailed at the register-transfer level, and a command-set is specified. Suggestions are offered for the transformation of this concept into working hardware.

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I. INTRODUCTION

Many information-processing tasks in the Air Force involve logical rather than numerical data. Digital computers, however, are organized in a way that is ill-suited to the lengthy combinatorial processes involved in logical computation. An early attempt to design a machine better suited to the needs of logical processing was that of Shannon and Moore [54] in 1953; they observed that "it seems to be typical of combinatorial problems that a tremendous gain in speed is possible by the use of special rather than general-purpose computers."

The economics of digital hardware today is such that there is little reluctance to attach a special-purpose processor to a general-purpose computer if distinctly faster processing results. This is especially true for military applications in which speed is crucial; the employment of FFT processors for real-time filtering is a well-known example. A logical processor of genuine utility has not appeared, however--in spite of the fundamental importance of logical processing, the exorbitant time required to do such processing in a general-purpose machine, and the obviously "logical" nature of digital technology. Although many logic-machines have been built, their applications have been confined for the most part to such fields as artificial intelligence, theorem-proving, and puzzle-solving.

The reason no practical machine for logical processing has been designed, in the author's opinion, is that there has not hitherto existed a general theory of logical processing. No "logical" von Neumann seems to have come along, in other words, to provide the plan for a machine to do general kinds of processing on propositions (rather than numbers). It is the author's contention, however, that such a plan did indeed present itself, but that it did so a little too soon to be noticed. It appeared in a dissertation entitled "Canonical Expressions in Boolean Algebra," published by A. Blake at the University of Chicago in 1937 [2].

Blake's dissertation should be remarkable especially to computer engineers and switching theorists because it defined the prime implicants of a Boolean function (without using the name) and discussed all of the basic techniques now known for computing prime implicants. The concept of a prime impli-

cant is invariably attributed in the literature on logical design to a paper by Quine [47] that appeared fifteen years after Blake's dissertation.

Quine applied the prime implicants of a Boolean function ϕ to find a simplified formula for ϕ. Blake's application for the prime implicants of ϕ, on the other hand, was far more general: he used them as a complete and simplified representation of all possible conclusions that can be inferred from the Boolean equation $\phi = 0$. Boole showed in Chapter VII of The Laws of Thought [3] that any system of logical propositions is reducible to the single equation $\phi = 0$; thus, Blake provided a satisfactory resolution of the general problem of deduction in propositional logic.

The Proposed Processor

This report describes the design and some of the possible applications of an inferential processor, a digital machine that mechanizes Blake's approach to logical deduction. The processor's function is to extract useful information, as requested in the program of a general-purpose computer, from a logical database.

The processor is attached as an adjunct to a general-purpose (host) computer. Its operation, after receipt of a system of propositions (expressed as Boolean equations), proceeds in three major phases: (1) reduction of the system to a single equation of the form $\phi = 0$; (2) generation of the prime implicants of ϕ; and (3) analysis of $\phi = 0$, i.e., employment of the prime implicants of ϕ to effect whatever deductive process the computer calls for.

Phase (1), as noted earlier, was described by Boole. Phase (2) has been the subject of intensive research by switching theorists for more than a quarter-century, inspired by the desire to simplify Boolean functions. Phase (3), however, seems totally unknown to logical designers. There is only one paper in the engineering literature, to the author's knowledge--a discussion [17] of keys in relational databases--that applies prime implicants to any form of deduction.

We believe that the design proposed in this report, while needing much in the way of definition and refinement, has the essential features of a machine that is "general-purpose" within the domain of Boolean algebra and, more specifically, of propositional logic.

Background

The history of inference-by-machine dates from the "Demonstrator" of the Earl of Stanhope, built around 1820. This device, and others built since, are described in Martin Gardner's book, Logic Machines and Diagrams [22].

Digital technology, with its strong ties to logic, has understandably inspired many "logical" processors. Chief among these have been theorem-verifiers [1,9,10,38,39,40,41], formula-minimizers [19,20,23,24,26,37], and equation-solvers [16,34,35,36,55,56]. Most of these machines have very specialized application and little direct bearing on the processor discussed in this report. The first serious attempt to formulate the principles of a logic-machine of wide applicability, based on electronic digital technology, was apparently that of Ledley [32]. Among his observations concerning the potential utility of such a machine are the following: "The propositional calculus can be applied to many phases of military science and related problems as well as to business, industry, science, and government in general. In these applications it serves as an aid to complex reasoning, e.g., in the analysis and evaluation of intelligence reports, the preparation and analysis of tactical methods and principles, the formulation of psychological and intelligence examinations, and the formulation and evaluation of business methods and procedures. All of these and similar 'reasoning' activities and operations can use the propositional calculus in a fundamental way. More well-known are its applications to the design of industrial process-control machines, digital computers, large-scale switching circuitry, and other forms of information-handling systems. However, the computational methods of the propositional calculus present serious and frequently insurmountable difficulties in the solution of actual problems, and this factor has severely limited its practical utilization....Consequently the need arises for a systematic method of formulating, analyzing, and solving propositional functions and equations. To solve practical problems, however, a large number of variables and extensive calculations are often needed. Thus it is also desirable for the logical methods to be amenable to easy mechanization, so that high-speed electronic 'logic machines' can be constructed to facilitate the calculations.... When it is desired to handle a large number of elements or propositions, a specialized, high-speed, electronic, digital logic machine will probably prove most effective.... The operations such a machine might contain are: simplification in either the simplest sum of products or

product of sums form; transformation to the absolute simplest form; checking statements for consistency, contradictions, redundancies, implications, or tautologies; generating all implications from a given hypothesis; making changes of variables; and solving logical equations."

An attempt to design a machine of the kind described by Ledley was begun at UCLA in about 1968 under the sponsorship of the Office of Naval Research. The group at UCLA, headed by Antonin Svoboda (well known for his early work on computing mechanisms and his pioneering work on residue arithmetic), proposed to construct a machine called a "Boolean Analyzer" [55]. Conceived specifically for Boolean processing, the Boolean Analyzer was to be an adjunct to a general purpose computer; among other things, it was to be capable of solving Boolean equations. The Boolean Analyzer, like Ledley's logic-machine, was never constructed. A number of APL programs have been written, however, to carry out the functions intended for the Boolean Analyzer. These programs are the basis for a recent book by Svoboda and White [58] which is essentially a manual for applying the Boolean Analyzer as a sophisticated tool for the design of digital circuits. Included in that book are details on the logical design of the proposed UCLA machine.

Research by the author [8] has revealed that the prime implicants of ϕ provide a very convenient way to produce a general solution of the Boolean equation $\phi = 0$. A machine to carry out this process has been described in a thesis by Toon [59].

Overview of the Report

Section II, which follows, outlines the objectives of the project. Section III presents the concepts of Boolean analysis--some classical, some new--which underlie the design and application of the proposed processor. Sections IV, V and VI treat the hardware organization of the processor. Section IV is an overall description; the two following sections discuss its major components, the minterm-processor (Section V) and the term-processor (Section VI). Section VII discusses specific applications for the processor, viz., solution of Boolean equations, the detection of functional deducibility, selective deduction, and the location of faults in digital systems. Finally, Section VIII provides a number of recommendations and suggestions for future work.

II. OBJECTIVES

Logical processing is required to solve many problems arising in command and control, the analysis of intelligence-data, the supervision of operational systems and processes, and a variety of other military, industrial, commercial and scientific applications. The use of computers for such processing has seldom, however, entailed formal or systematic techniques of logical inference.

Three factors appear to inhibit the application of such techniques:

(a) the absence of a unified approach to the formulation of inferential problems and the mechanization of their solution;

(b) the excessive time required for general-purpose computers to execute the combinatorial computation-chains inherent in logical processing; and

(c) a lack of information, resulting in part from factors (a) and (b) above, concerning the application of inferential techniques to problems of practical interest.

This project has three corresponding objectives:

A. To develop a unified approach to the mechanization of inferential processes.

B. To work out the principles of design of a high-speed inferential processor.

C. To determine the utility of such a processor in the solution of practical problems.

III. BOOLEAN ANALYSIS

Information is supplied to the inferential processor in the form of systems of Boolean equations. We use the term Boolean analysis to denote the process of extracting conclusions, in some specified form, from such systems.

Suppose, for example, that a certain situation involves logical variables A, B, C, and D, and that the following conditions are known to exist:

1. If C is true, then A is true.
2. A is true and B is false if and only if either C is false or D is false (or both).
3. B and D cannot be true simultaneously.
4. If C is false, then either A or B (but not both) is true.

Suppose further that it is desired to find a complete and simplified set of conclusions that may be inferred from statements 1 through 4 above.

The first step in obtaining the desired set of conclusions is to transmit the foregoing statements to the inferential processor as Boolean equations, essentially in the form shown below (the precise format is discussed in Section V).

$$\begin{aligned} &1. \quad C \leq A \\ &2. \quad A\bar{B} = \bar{C} + \bar{D} \\ &3. \quad BD = 0 \\ &4. \quad C \leq \bar{A}B + A\bar{B} \quad . \end{aligned} \tag{3.1}$$

After receiving the foregoing system of equations, and on a request from the user for output, the processor prints the expression

$$\bar{A} + B + CD \quad . \tag{3.2}$$

Every formula stored by the inferential processor, or printed as output, is the left-hand member of an assumed equation whose right-hand member is 0. A property of Boolean algebras, moreover, is that a sum is equal to zero if and only if each of its summands is equal to zero. Hence, (3.2) represents the

system

$$\bar{A} = 0$$
$$B = 0 \qquad (3.3)$$
$$CD = 0 \quad .$$

We call each of the foregoing equations a prime conclusion of the system (3.1); the equations in (3.3) constitute the complete and simplified set of conclusions originally sought (the sense in which these conclusions are complete and simplified is explained later in this section). The system (3.3) is equivalent to (i.e., it expresses precisely the same information as) the system (3.1).

In practical applications, the user is seldom likely to be interested in simple deduction of the sort carried out above. The number of prime conclusions, moreover, may be very large in a practical problem--sometimes many thousands in applications involving ten or fifteen variables. Normally, therefore, the processor would not be commanded simply to print prime conclusions. A central design-feature of the proposed processor, nevertheless, is that it generates and stores all of the prime conclusions internally, using them to carry out the various more practical operations of Boolean analysis.

A somewhat more representative problem than the simple deductive one just discussed would be the following: given the system

$$\begin{aligned} x_4 &= x_1x_2 + x_1x_3 + x_2x_3 \\ x_5 &= x_1 \oplus x_2 \oplus x_3 \\ x_6 &= x_1x_2\bar{x}_5 + \bar{x}_1\bar{x}_2x_5 \end{aligned} \qquad (3.4)$$

of equations defining a certain digital system, find a simplified expression for x_6 in terms of the variables $x_1, x_2, \ldots, x_5$ (this is the problem of optimum design of the overflow-output in a two's-complement adder; see Section VII for details). The system (3.4) produces 66 prime conclusions, which would be of little use to a designer seeking a simplified formula for x_6; after receiving the commands discussed in Section VII, however, the processor is able to use these conclusions to determine that x_6 may be expressed by the formula

$$x_3 \oplus x_4 \ .$$

The latter formula is clearly simpler than the one given in (3.4) for x_6 (curiously, it involves none of the variables appearing in the original formula).

Another application would be that of supervising the location, on-line, of faults in a digital system. In such an application, the processor would be provided initially with a logical database, i.e., a collection of prime conclusions representing what it "knows" at the outset concerning the system under diagnosis. The processor would decide upon, and apply, a stimulus to the system--after which it would observe the response and update its logical database. The processor would then repeat the test-observe-update cycle, continuing to accumulate information in this way until no more can be elicited. The crucial feature of the foregoing process is that the input selected by the processor on each cycle is guaranteed to produce new information; in the typical case, therefore, only a small fraction of the possible tests is actually carried out before the processor announces that it has found out all that can be known as the result of input-output testing. To complete the diagnostic process, the processor informs the user of the set of fault-configurations (none, if the system is free of faults) that are compatible with the observed input-output behavior. This application is discussed in more detail in Section VII; a full report [7] has been completed separately.

The foregoing examples are intended to give a general impression of the kind of processor we seek to design. The design itself is based on certain results in the field of Boolean algebra; some of these results are available in the literature (see, e.g., [51]), but are not generally known to digital engineers; others have arisen out of the author's investigations over the past ten years. These results fall into a pattern leading to a systematic and comprehensive theory of Boolean analysis (not attempted in this report) and providing the basis for the design of logical processors of very general capability.

The present section attempts an organized discussion of some of the more important of the concepts just alluded to (those having specialized application are presented informally or tacitly in succeeding sections). The reader is presumed to be generally familiar with the concepts and notation of Boolean algebra, especially with those (truth-tables, minterms, prime implicants, etc.) that are commonly employed in digital engineering; we review some of the latter ideas, nevertheless, in order to fix nomenclature.

Elementary Properties and Terminology

The data supplied to the inferential processor involve variables, usually represented in this report by the symbols $x_1, x_2, \ldots, x_n$. In some applications, these variables denote logical propositions; more generally, they may denote elements of an arbitrary Boolean algebra, e.g., a class-algebra or switching algebra. We do not make a careful distinction between propositions and elements of a general Boolean algebra, and we use the notation of Boolean algebra uniformly. In particular, we translate the relations $\longrightarrow$ (implication) and $\longleftrightarrow$ (equivalence) of the calculus of propositions into the relations $\leq$ (inclusion) and = (equality), respectively, of Boolean algebra. At the beginning of this section, for example, we translate the statement "If C is true, then A is true," denoted by $C \rightarrow A$ in the calculus of propositions, into the statement $C \leq A$ in the system (3.1).

The basic rules of Boolean algebra, expressed in terms of the operations AND (· or juxtaposition), OR (+), and NOT ($\bar{\ }$), will be presumed to be familiar to the reader. We define the inclusion-relation $\leq$ by the equivalence

$$a \leq b \Leftrightarrow a\bar{b} = 0 \ . \tag{3.5}$$

Two other equivalences valid for Boolean algebras, viz.,

$$a = b \Leftrightarrow a \oplus b = 0 \tag{3.6}$$

$$a = 0 \ \text{ and } \ b = 0 \Leftrightarrow a + b = 0 \ , \tag{3.7}$$

are of fundamental importance in the operation of the inferential processor. All three of the foregoing equivalences are standard results in Boolean algebra. The significance of equivalences (3.5) and (3.6) is that they enable an equation (a term we use henceforth to include not only an equation in the strict sense, but also an inclusion) to be represented as a function. This representation is used uniformly in the inferential processor; every function ϕ stored in the processor is taken to be the left member of the equation $\phi = 0$. Equivalence (3.7) enables a system of equations to be represented as a single function. The system

$$\begin{aligned} p &\leq q \\ r &= s \ , \end{aligned} \tag{3.8}$$

for example, is represented in the inferential processor by the function

$$p\bar{q} + (r \oplus s) \ . \tag{3.9}$$

A single variable, complemented or uncomplemented, will be called a literal. A term is either 1, a single literal, or a product of literals in which no variable appears more than once. A minterm is a term in which all n variables appear exactly once. An SOP (sum-of-products) formula is a single term or a sum of terms.

The word function will refer consistently to an n-variable switching function, i.e., a mapping $\emptyset: \{0,1\}^n \longrightarrow \{0,1\}$. A function may be specified by a truth-table, such as the one shown below for $n=3$.

x_1	x_2	x_3	$\emptyset(x_1,x_2,x_3)$
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

The elements in the function-column of a truth-table will be called the minterm-coefficients of the function. The array of minterm-coefficients of a function $\emptyset$ provides a representation of $\emptyset$ suitable for digital storage; thus, the function whose truth-table is shown above can be represented by (stored as) the array $\emptyset$ = 01110011 .

An implicant of a function $\emptyset$ is a term p such that $p \leqslant \emptyset$. A prime implicant of $\emptyset$ is an implicant p of $\emptyset$ such that, for any term q, $p \leqslant q \leqslant \emptyset \implies p = q$. A prime implicant of $\emptyset$, therefore, is an implicant of $\emptyset$ none of whose proper sub-terms (sub-products) is an implicant of $\emptyset$.

The inferential processor employs two internal representations for storage and manipulation of a Boolean function $\emptyset$. The first is by means of the 2^n minterm-coefficients of $\emptyset$, discussed above. The second representation is in terms of the prime implicants of $\emptyset$. The sum of all of the prime implicants of a Boolean function is an SOP formula representing that function; we devote the remainder of the present section to a discussion of the properties and applications of that SOP formula.

The Blake Canonical Form

One of the most useful canonical forms for a Boolean function is the sum of all of its prime implicants. The term "prime implicant," as well as the theory of systematic formula-minimization in terms of prime implicants, comes from a paper by W. V. Quine [47] in 1952; however, a dissertation fifteen years earlier by A. Blake [2] anticipated much of the later theory concerning prime implicants, and established basic results on their application in logical inference that still have not been re-discovered.

Blake showed that the sum of all prime implicants is a canonical form; moreover, he showed that this form can be used as a condensed representation of all the consequences of a collection of logical propositions. In doing so, Blake provided a satisfactory solution for one of the principal problems of propositional logic, replacing the equation-solving techniques of Boole [3] and Schröder [53], and the elaborate tabular methods of Poretsky [46], by the relatively simple process of calculating the prime implicants of a propositional function. An aspect of Blake's approach was rediscovered by Robinson [50] in 1965 in the context of the first-order predicate calculus, where it is called the "resolution principle." This principle is the basis for virtually all current work on mechanical theorem-proving [15, 33, 44].

We shall call the sum of all the prime implicants of a Boolean function ϕ the Blake canonical form for ϕ and denote it by BCF(ϕ).

The proposed inferential processor is basically a machine to mechanize Blake's approach to logical deduction. This approach seems totally unknown to machine-designers and switching theorists; consequently, no machine to date has been designed to utilize the Blake canonical form for purposes of logical inference. A number of machines [19, 24, 26] have incorporated specialized hardware for generating prime implicants, but only (following Quine) to produce simplified formulas. The designers of these machines have given considerable thought to the problem of generating and storing prime implicants efficiently; their work, especially that of Gerace, et al. [24], has proved most helpful in working out the design of the proposed inferential processor.

Generating BCF(ϕ). The concepts of design and application discussed in this report are essentially independent of the algorithm implemented in the inferential processor to generate prime implicants. By far the majority of the

memory-capacity and processing-time of the processor, however, will be devoted to that algorithm. Indeed, the basic reason for putting inferential processing in hardware, rather than programming it in a general-purpose computer, is to achieve a drastic reduction in the time required to generate prime implicants (Gerace, et al., report a 100-to-1 reduction). Much of the effort in this project, therefore, went into defining the prime-implicant algorithm. The algorithm itself will not be described here, inasmuch as it is complex and some details remain to be worked out. We shall outline, however, the general problem of generating prime implicants in hardware.

The set of prime implicants of an n-variable function ϕ is a subset of the 3^n terms on n variables. A direct approach to the generation of BCF(ϕ), therefore, is to generate all 3^n terms, retaining the terms that (i) are found to be implicants of ϕ and (ii) are not included in other terms that are implicants of ϕ. At least two logic-machines, those of Florine [19] in Belgium and Gómez-González [26] in Spain, generate prime implicants in this way. The Florine machine generates all 3^n terms; the Gómez-González machine stops generating terms when certain conditions are met.

Although the foregoing method is simple in conception, and readily implemented in hardware for low values of n, the number of candidate-terms that must be stored while searching for prime implicants (and the time required for the requisite scanning) rises rapidly with n. If n is 16, for example (a modest value for practical applications), the number of terms exceeds 43 million; if n is 20, the number of terms is about 3500 million.

Fortunately, a vast quantity of research over the past quarter-century has been devoted to finding alternative, and more efficient, methods for finding prime implicants. Two basic approaches, <u>iterated consensus</u> and <u>multiplying</u>, have emerged out of this work. (It seems not to be known that both methods were presented in Blake's dissertation.)

The first basic approach--iterated consensus--was discovered independently by Samson and Mills [52], to whom it is generally attributed, and by Quine [48]. A specialization of this method, which might be called iterated consensus of minterms, was given by Quine [47]; this method, discussed in most textbooks on logical design, has some bookkeeping advantages over the general method of iterated consensus, but requires a preliminary development of ϕ into its minterms. The method of iterated consensus is best understood in terms of logical inference, which we discuss in the next subsection; we there-

fore postpone our explanation of iterated consensus, taking it up again in connection with logical inference.

The second basic approach--the method of multiplying--is usually attributed to Nelson [43], but was given in an earlier report by Samson and Mills [52]. As noted earlier, however, the priority belongs to Blake.

The approach chosen for implementation in the inferential processor is that of iterated consensus. In particular, we have decided to adopt the variation of iterated consensus mechanized in the logical computer TOPI, built in Italy by Gerace, et al. [24]. The TOPI algorithm is the only one of the many encountered by this investigator that attempts seriously to minimize the largest number of candidate-implicants that are stored during the process of generating prime implicants. Minimizing this number is crucial, because prime implicants consume by far the majority of the storage-space in the inferential processor (as well as in the other machines mentioned earlier), and this number, which increases rapidly with n in any case, varies widely from one algorithm to another.

Logical Inference

We present in this subsection a summary of Blake's technique for mechanizing logical inference. This technique is applicable to Boolean algebras in general and to the calculus of propositions in particular.

Blake's object was to determine the inferences that may be drawn from the statement $\phi = 0$, where ϕ is a Boolean function. His procedure was to represent the function ϕ by a canonical form, BCF(ϕ), viz., the sum of all the prime implicants of ϕ (the term "prime implicant" was invented by Quine [47] fifteen years after Blake's dissertation was published). From this canonical form, inferences (conclusions) can be

(i) <u>generated</u> systematically, and
(ii) <u>validated</u> by inspection.

In traditional logic (the logic of textbooks and university courses), deduction is carried out by invoking a number of rules of inference; these rules announce that certain conclusions follow from certain sets of premises. Some texts, e.g., [30], list hundreds of such rules. One of the cardinal ad-

vantages of Blake's method is that there is only one rule of inference. This method can be developed rigorously within the framework of Boolean algebra; however, the essential idea can be grasped by examining one of the central inference-rules in traditional logic, that of hypothetical syllogism. This rule states that the conclusion given below follows from its premises (we express the components of this syllogism both as propositions and as equations).

	Proposition	Equation
Major Premise:	$A \rightarrow B$	$A\overline{B} = 0$
Minor Premise:	$B \rightarrow C$	$B\overline{C} = 0$
Conclusion:	$A \rightarrow C$	$A\overline{C} = 0$

The two premises may be expressed by the single equation

$$\phi = 0, \tag{3.10}$$

where ϕ is given by

$$\phi = A\overline{B} + B\overline{C} \quad . \tag{3.11}$$

The conclusion is expressed by the equation

$$\psi = 0, \tag{3.12}$$

where

$$\psi = A\overline{C} \ . \tag{3.13}$$

The problem of deduction in this case is to obtain the term $A\overline{C}$ (representing the conclusion) from the terms $A\overline{B}$ and $B\overline{C}$ (representing the premises). Let us say that a variable is opposed in two terms if it appears complemented in one term and uncomplemented in the other. Blake noted that the term $A\overline{C}$ is obtained by simply multiplying $A\overline{B}$ and $B\overline{C}$, deleting the opposed literals $\overline{B}$ and B. More formally,

Definition 3.1. If two terms p and q are opposed in exactly one variable, then the consensus of p and q is the term obtained from pq by

(i) deleting the two opposed literals, and
(ii) deleting any repetitions.

Blake used the term "syllogistic result" rather than "consensus," but the latter term, applied by Quine [48] in 1955, is now universally accepted.

The consensus-operation appears at first to be a somewhat elaborate way to find the conclusion in a hypothetical syllogism. Blake showed, however, that this one operation suffices to produce a simplified representation of <u>all</u> conclusions to be inferred from <u>any</u> set of premises in propositional logic.

Before discussing the production of conclusions from given premises, let us show how the operation of consensus may be used to produce prime implicants. Let ϕ be a Boolean function. The following algorithm, customarily called <u>iterated consensus</u>, generates BCF(ϕ):

1. Express ϕ as an SOP formula.
2. Persevere in these two equivalence-transformations:
   (a) if a term is included in (i.e., has all the literals of) another term, drop the former.
   (b) Adjoin, as an additional term, the consensus of two terms, unless it is included in a term already present.

The wording above is essentially Quine's [48]. The method is today usually attributed to Samson and Mills [52], but it was given by Blake in his dissertation seventeen years earlier.

<u>Prime conclusions</u>. We assume henceforth that all Boolean functions are expressed as SOP formulas. An equation $\psi = 0$ is a <u>conclusion</u> of the equation $\phi = 0$ if and only if the function ψ is included in the function ϕ, i.e., if and only the relation $\psi \leq \phi$ is valid. Thus, <u>the problem of finding conclusions of $\phi = 0$ reduces to that of finding Boolean functions included in ϕ</u>.

The problem of generating SOP formulas included in a given SOP formula ϕ, or of deciding whether a given SOP formula is included in ϕ, is not in general easy. It is not obvious, for example, that the function

$$\psi = B\bar{C}D + A\bar{D} \qquad (3.14)$$

is included in the function

$$\phi = A\bar{C} + C\bar{D} + \bar{A}D \ . \qquad (3.15)$$

The problem becomes much easier, however, if we confine ourselves to a specialized kind of inclusion defined by Blake as follows.

Definition 3.2. Let ϕ and ψ be SOP formulas. We say that ψ is formally included in ϕ, written $\psi \ll \phi$, in case each term of ψ is included in (i.e., has all the literals of) some term in ϕ.

Given SOP formulas ψ and ϕ, one can tell by inspection if ψ is formally included in ϕ; moreover, the set of SOP formulas formally included in ϕ can be generated in a simple and systematic way. These advantages appear to be of little utility in logical deduction, nevertheless, because a formula that is included in ϕ (representing a conclusion of $\phi = 0$) may not be formally included in ϕ. The function (3.13), for example, is included in (3.11), as application of the definition (3.5) will verify; also, the function (3.14) is included in (3.15). In neither of the foregoing cases does the relation of formal inclusion hold. Blake proved, however, that inclusion in ϕ and formal inclusion in ϕ coincide provided ϕ is expressed as the sum of all of its prime implicants. Stated more precisely,

Proposition 3.1. Let ψ and ϕ be SOP formulas. Then ψ is included in ϕ if and only if ψ is formally included in BCF(ϕ).

Returning to the hypothetical syllogism, let us express the function (3.11), representing the premises, in Blake canonical form:

$$\mathrm{BCF}(\phi) = A\overline{B} + B\overline{C} + A\overline{C} \quad . \tag{3.16}$$

It is clear that the function $\psi = A\overline{C}$, corresponding to the conclusion, is formally included in BCF(ϕ). Returning to another example, the Blake canonical form for the function (3.15) is found by iterated consensus to be

$$\mathrm{BCF}(\phi) = A\overline{C} + C\overline{D} + \overline{A}D + A\overline{D} + \overline{C}D + \overline{A}C \quad . \tag{3.17}$$

The formula (3.14) is formally included in (3.17) because the terms $B\overline{C}D$ and $A\overline{D}$ of (3.14) are included, respectively, in the terms $\overline{C}D$ and $A\overline{D}$ of BCF(ϕ).

Let a function ϕ have prime implicants $p_1, p_2, \ldots, p_k$. We shall call the equations

$$\begin{aligned} p_1 &= 0 \\ p_2 &= 0 \\ &\vdots \\ p_k &= 0 \end{aligned}$$

the __prime__ __conclusions__ of the Boolean equation $\phi = 0$. As we have seen, any conclusion of $\phi = 0$ expressed in the form $\psi = 0$, where ψ is an SOP formula, can be built up directly from the prime conclusions; no simpler set of conclusions, moreover, will suffice to build up all conclusions.

The prime conclusions of the hypothetical syllogism, for example, are

$$A\overline{B} = 0$$

$$B\overline{C} = 0$$

$$A\overline{C} = 0 \quad .$$

In this case, the prime conclusions consist of the two premises, together with the associated conclusion. Typically, however, the prime conclusions do not bear such a direct relationship to the premises that generate them. The three prime conclusions displayed in (3.3), for example, have no immediately discernible relation to the set (3.1) of premises. In all cases, however, the premises themselves are conclusions--whose validity can be checked by testing for formal inclusion in BCF(ϕ). Returning to the system (3.1) of premises, the corresponding Blake canonical form is given in (3.2), viz.,

$$\mathrm{BCF}(\phi) = \overline{A} + B + CD. \qquad (3.18)$$

Let us test premise 2 of the system (3.1), which is equivalent to the equation

$$\psi = 0 \ ,$$

where ψ is given by

$$\psi = A\overline{B}CD + \overline{A}\,\overline{C} + \overline{A}\,\overline{D} + B\overline{C} + B\overline{D} \ . \qquad (3.19)$$

Each term of (3.19) is included in a term of (3.18); hence, premise 2 of (3.1) is a valid conclusion (as any premise must be).

Let us consider a final example, taken from a well-known text [30] on formal logic. The following statements describe a student, Alfred:

1. If Alfred studies, then he receives good grades.
2. If Alfred doesn't study, then he enjoys college.
3. If Alfred doesn't receive good grades, then he doesn't enjoy college.

What can we conclude about Alfred?

The foregoing premises are expressed by the system

$$\begin{aligned} &1. \quad S\bar{G} = 0 \\ &2. \quad \bar{S}\bar{E} = 0 \\ &3. \quad \bar{G}E = 0 \end{aligned} \tag{3.20}$$

of Boolean equations, where

E = "Alfred enjoys college"

G = "Alfred gets good grades"

S = "Alfred studies" .

The system (3.20) is equivalent to the single equation $\phi = 0$, where

$$\phi = S\bar{G} + \bar{S}\bar{E} + \bar{G}E \; . \tag{3.21}$$

In Blake canonical form,

$$\phi = \bar{S}\bar{E} + \bar{G} \quad . \tag{3.22}$$

The prime conclusions corresponding to (3.22) may be put in verbal form as follows:

(a) If Alfred doesn't study, then he enjoys college.

(b) Alfred gets good grades.

These two prime conclusions constitute a complete and simplified statement of the information contained in the three original premises. In this case, one premise (the second) in (3.20) survives as a prime conclusion.

The proposed inferential processor mechanizes the approach to logical deduction described above, proceeding in three major phases:

(1) reduction of a system of equations to a single equation of the form $\phi = 0$;

(2) generation of the prime implicants of ϕ, and

(3) analysis of $\phi = 0$.

The first two phases are carried out automatically by the processor on any system of equations it receives. The third phase--analysis--is governed by the user, who may call for $\phi = 0$ to be processed in any of a variety of ways described in Sections VI and VII. If the user wishes to know only the prime

conclusions, then analysis is complete after phase (2). Typically, however, the user is interested in a restricted aspect of the information inherent in the original system of equations. The author's research over the past few years has indicated that virtually any aspect of that information can be retrieved conveniently from BCF(ϕ).

One of the useful ways to extract information from a system of equations is to solve the system for a given subset of the variables in terms of another subset, perhaps eliminating a third subset. The Blake canonical form provides a convenient avenue to the solution of Boolean equations; that avenue is followed in the remainder of this section.

Boolean Equations

We present in the following paragraphs a summary of those portions of the theory of Boolean equations relevant to the design and application of the inferential processor. We focus on the operations of reduction, elimination, and solution; see [27] or [51] for a complete treatment of the classical theory. The applications of the Blake canonical form to elimination and solution (thereby enabling the inferential processor to produce particular and general solutions of Boolean equations) are results of the author's research.

Reduction. Let us consider a system

$$\begin{aligned} s_1(\underline{u},\underline{v}) &= t_1(\underline{u},\underline{v}) \\ &\vdots \\ s_k(\underline{u},\underline{v}) &= t_k(\underline{u},\underline{v}) \\ s_{k+1}(\underline{u},\underline{v}) &\leq t_{k+1}(\underline{u},\underline{v}) \\ &\vdots \\ s_p(\underline{u},\underline{v}) &\leq t_p(\underline{u},\underline{v}) \end{aligned} \tag{3.23}$$

of Boolean equations. The arguments are partitioned into two subvectors $\underline{u} = (u_1,\ldots,u_q)$ and $\underline{v} = (v_1,\ldots,v_r)$ for convenience in subsequent discussion.

A classical result in the theory of Boolean equations, first announced in Chapter VII of Boole's Laws of Thought [3], is that the system (3.23) may be reduced to a single equivalent equation,

$$\phi(\underline{u},\underline{v}) = 0 , \tag{3.24}$$

where the Boolean function ϕ is given by

$$\phi = \sum_{i=1}^{k} (g_i \oplus h_i) + \sum_{i=k+1}^{p} g_i \bar{h}_i . \tag{3.25}$$

The system (3.23) is also equivalent to the single equation

$$\psi(\underline{u},\underline{v}) = 1 , \tag{3.26}$$

where

$$\psi = \bar{\phi} = \prod_{i=1}^{k} (\bar{g}_i \oplus h_i) \cdot \prod_{i=k+1}^{p} (\bar{g}_i + h_i). \tag{3.27}$$

The equivalence of (3.23), (3.24), and (3.26) follows from relations (3.5), (3.6) and (3.7).

<u>Example</u> <u>3.1</u>. The system (3.1) is equivalent to the equation

$$\phi(A,B,C,D) = 0 , \tag{3.28}$$

where ϕ is given by the formula

$$\phi = C\bar{A} + (A\bar{B} \oplus (\bar{C} + \bar{D})) + (BD \oplus 0) + \bar{C}\cdot\overline{(\bar{A}B + A\bar{B})} \quad . \tag{3.29}$$

The Blake canonical form BCF(ϕ) is displayed in (3.2).

<u>Elimination</u>. Let $\phi(\underline{u},\underline{v})$ be a Boolean function having sub-arguments $\underline{u}$ and $\underline{v}$ as defined before. We define the <u>zero</u>-<u>eliminant</u> and <u>one</u>-<u>eliminant</u> of ϕ with respect to $\underline{u}$, denoted $e_{\underline{u}}\phi$ and $E_{\underline{u}}\phi$, respectively, as follows:

$$(e_{\underline{u}}\phi)(\underline{v}) = \phi(0,\ldots,0,0,\underline{v})\cdot\phi(0,\ldots,0,1,\underline{v})\cdot\cdots\cdot\phi(1,\ldots,1,1,\underline{v}) \tag{3.30}$$

$$(E_{\underline{u}}\phi)(\underline{v}) = \phi(0,\ldots,0,0,\underline{v}) + \phi(0,\ldots,0,1,\underline{v}) + \ldots + \phi(1,\ldots,1,\underline{v}). \tag{3.31}$$

A pair of eliminants of ϕ with respect to $\underline{v}$, $e_{\underline{v}}\phi$ and $E_{\underline{v}}\phi$, may be similarly defined. Eliminants with respect to $\underline{u}$ are clearly functions of $\underline{v}$ alone; eliminants with respect to $\underline{v}$, on the other hand, are functions of $\underline{u}$ alone.

The equation

$$(e_{\underline{u}}\phi)(\underline{v}) = 0 \tag{3.32}$$

is called the <u>resultant</u> <u>of</u> <u>elimination</u> of $\underline{u}$ from (3.24); likewise, the equation

$$(E_{\underline{u}}\psi)(\underline{v}) = 1 \tag{3.33}$$

is the resultant of elimination of u from (3.26). Either of these equivalent equations expresses all that may be deduced from (3.24) concerning v, in the absence of knowledge concerning u.

As noted earlier, the inferential processor works consistently with an equation of the form $\phi = 0$; thus equation (3.26) and its associated resultant of elimination (3.33) are not of direct interest. The author's research has shown, however, that the function $E_u \phi$ has important deductive applications in a system processing equations only of the form $\phi = 0$. Among these applications are the detection of functional deducibility and the location of stuck-type faults in digital circuits (see Section VII).

Example 3.2. The equation

$$z = xy \tag{3.34}$$

specifies the behavior of an AND-gate having inputs x and y and output z. Equation (3.34) is equivalent to either of the equations

$$\phi(x,y,z) = 0 \tag{3.35}$$

$$(x,y,z) = 1 \; , \tag{3.36}$$

where

$$\phi = xy\bar{z} + \bar{x}z + \bar{y}z \tag{3.37}$$

$$\bar{\phi} = xyz + \bar{x}\bar{z} + \bar{y}\bar{z} \; . \tag{3.38}$$

The eliminants $e_x \phi$ and $E_x \psi$ are given by

$$e_x \phi = \phi(0,y,z)\ \phi(1,y,z) = \bar{y}z \tag{3.39}$$

$$E_x \psi = \psi(0,y,z) + \psi(1,y,z) = y + \bar{z} \; . \tag{3.40}$$

The resultants of elimination of x from equations (3.35) and (3.36) are therefore (in order) the equations

$$\bar{y}z = 0 \tag{3.41}$$

$$y + \bar{z} = 1 \; . \tag{3.42}$$

Either of the foregoing equations expresses all that is known concerning the operation of the AND-gate if the value of the input x is unknown.

Formulas (3.30) and (3.31) defining the zero-eliminant and one-eliminant of ϕ with respect to u are inconvenient for mechanization in a digital machine.

The two propositions which follow are the basis for computation of eliminants in the inferential processor. Proposition 3.2, proved in [4], enables $e_{\underline{u}}\phi$ to be found by deleting a conveniently-determined subset of the prime implicants of ϕ. Proposition 3.3 enables $E_{\underline{u}}\phi$ to be generated conveniently from any SOP formula for ϕ, in particular from BCF(ϕ); the first statement of Proposition 3.3 was apparently Mitchell's [42] in 1883.

Proposition 3.2.

$$e_{\underline{u}}\phi(\underline{u},\underline{v}) = \sum \begin{pmatrix}\text{prime implicants of } \phi(\underline{u},\underline{v}) \\ \text{not involving u-variables}\end{pmatrix} \tag{3.43}$$

Example 3.3. Let a Boolean function ϕ be represented by the formula

$$\begin{aligned}\phi(u_1,u_2,u_3,v_1,v_2) = {} & u_1\bar{v}_1v_2 + \bar{u}_1\bar{u}_2v_1 + \bar{u}_1u_3v_2 + \\ & u_1u_3v_1 + \bar{u}_3v_1\bar{v}_2 + u_2u_3v_1 \;.\end{aligned} \tag{3.44}$$

If ϕ is re-expressed in Blake canonical form, viz.,

$$\text{BCF}(\phi) = u_1\bar{v}_1v_2 + \bar{u}_1\bar{u}_2v_1 + u_3v_2 + u_3v_1 + v_1\bar{v}_2 \;, \tag{3.45}$$

then the eliminants $e_{\underline{u}}\phi$ and $e_{\underline{v}}\phi$ may be written by inspection:

$$e_{\underline{u}}\phi = v_1\bar{v}_2 \tag{3.46}$$

$$e_{\underline{v}}\phi = 0 \;. \tag{3.47}$$

Proposition 3.3. Let $\phi(\underline{u},\underline{v})$ be expressed by an SOP formula. Then $E_{\underline{u}}\phi$ is derived from that formula by replacing each u-literal ($\bar{u}_i$ or u_i, $i = 1,2,\ldots,q$) by 1.

Example 3.4. Let ϕ be the function given in example 3.3, expressed by the SOP formula (3.44). Then $E_{\underline{u}}\phi$ and $E_{\underline{v}}\phi$ are given by

$$E_{\underline{u}}\phi = \bar{v}_1v_2 + v_1 + v_2 + v_1 + v_1\bar{v}_2 + v_1 \tag{3.48}$$

$$E_{\underline{v}}\phi = u_1 + \bar{u}_1\bar{u}_2 + \bar{u}_1u_3 + u_1u_3 + \bar{u}_3 + u_2u_3 \tag{3.49}$$

which assume the simplified forms

$$E_{\underline{u}}\phi = v_1 + v_2 \tag{3.50}$$

$$E_{\underline{v}}\phi = 1 \;. \tag{3.51}$$

The SOP formula (3.45) leads to the same simplified forms.

Solutions. As before, let $\underline{u} = (u_1,\ldots,u_q)$ and $\underline{v} = (v_1,\ldots,v_r)$. In the present context, we call the u's the dependent variables and we call the v's the independent variables. A solution for $\underline{u}$ of the Boolean equation $\phi(\underline{u},\underline{v}) = 0$ is a vector $\underline{g} = (g_1,\ldots,g_q)$ of r-variable Boolean functions having the property that the equation

$$\phi(\underline{g}(\underline{v}),\underline{v}) = 0 \tag{3.52}$$

is an identity. It is of course common practice to write a solution for $\underline{u}$ in the form

$$\underline{u} = \underline{g}(\underline{v}) \ , \tag{3.53}$$

where $\underline{g}$ has the property specified above.

The equation $\phi(\underline{u},\underline{v}) = 0$ is said to be consistent with respect to $\underline{u}$ (or simply consistent) in case it has at least one solution. Consistency is decided by the following rule, first stated by Boole in Chapter VIII of [3].

Proposition 3.4. The equation $\phi(\underline{u},\underline{v}) = 0$ is consistent with respect to $\underline{u}$ if and only if $\underline{v}$ satisfies the equation

$$(e_{\underline{u}}\phi)(\underline{v}) = 0 \ . \tag{3.54}$$

Example 3.5. It was shown in Example 3.3 that $e_{\underline{u}}\phi = v_1\bar{v}_2$ for the function ϕ defined by (3.44). Thus, a vector $\underline{g} = (g_1(\underline{v}),g_2(\underline{v}),g_3(\underline{v}))$ may be found to satisfy $\phi(\underline{u},\underline{v}) = 0$ if and only if the condition $v_1\bar{v}_2 = 0$ is satisfied. Suppose the latter condition to be satisfied; then

$$\begin{aligned} u_1 &= v_1 \\ u_2 &= 1 \\ u_3 &= \bar{v}_2 \end{aligned} \tag{3.55}$$

may be verified by substitution to be a solution of $\phi = 0$. Substitution in (3.44) yields $\phi = v_1\bar{v}_2$ rather than $\phi = 0$; we have assumed, however, that $v_1\bar{v}_2 = 0$.

Solutions generated by the inferential processor. Let us very briefly outline the action of the inferential processor in solving a system of Boolean equations (this topic is treated at length in Secion VII). The processor is first loaded with the system of equations, using commands discussed in Section V. As the equations in the system are loaded, the processor develops a function ϕ (represented by its minterm-coefficients) having the property that $\phi = 0$ is

equivalent to the portion of the system already accepted. On receipt of a command indicating that loading of the system is complete, the processor uses the minterm-coefficients of ϕ to generate the Blake canonical form BCF(ϕ). The BCF representation of ϕ is the basis for virtually all of the deductive operations carried out by the processor, including that of solving $\phi(\underline{u},\underline{v}) = 0$ for $\underline{u}$ in terms of $\underline{v}$.

If the equation $\phi(\underline{u},\underline{v}) = 0$ is consistent, it typically has many solutions for $\underline{u}$. The inferential processor can be commanded to produce a general solution, which re··esents all of the possible solutions in condensed form; alternatively, it can be commanded to produce a particular solution, i.e., *one* solution from among those that exist.

The general solution produced by the inferential processor has the form

$$\begin{aligned} g_0(\underline{v}) &= 0 \\ g_1(\underline{v}) \leq u_1 &\leq h_1(\underline{v}) \\ g_2(u_1,\underline{v}) \leq u_2 &\leq h_2(u_1,\underline{v}) \\ &\vdots \\ g_q(u_1,\ldots,u_{q-1},\underline{v}) \leq u_q &\leq h_q(u_1,\ldots,u_{q-1},\underline{v}) . \end{aligned} \tag{3.56}$$

The first statement in the system (3.56) is the consistency condition, previously stated as (3.54); that is,

$$g_0(\underline{v}) = e_{\underline{u}}\phi \quad . \tag{3.57}$$

The second statement in (3.56) specifies the range of allowable values of u_1. For any value of u_1 in that range, the third statement specifies the range of allowable values of u_2, and so on.

The inferential processor employs the following algorithm, based on results proved in [8], to generate a general solution of the form (3.56) for the equation $\phi(\underline{u},\underline{v}) = 0$ (see Section VII for details on processor-commands and for an example.

Step 1. $F \leftarrow$ the set of prime implicants of ϕ.

Step 2. $i \leftarrow q$

Step 3. $g_i \leftarrow 0$

Step 4. If F has a member of the form $\bar{u}_i p$, where p is a term, then proceed; otherwise, go to Step 7.

Step 5. $g_i \leftarrow g_i + p$

Step 6. Delete $\bar{u}_i p$ from F and return to Step 4.

Step 7. Print g_i.

Step 8. If $i = 0$, go to Step 16; otherwise, proceed.

Step 9. $h_i \leftarrow 0$

Step 10. If F has a member of the form $u_i p$, where p is a term, then proceed; otherwise, go to Step 13.

Step 11. $h_i \leftarrow h_i + p$

Step 12. Delete $u_i p$ from F and return to Step 10.

Step 13. $h_i \leftarrow \bar{h}_i$

Step 14. Print h_i.

Step 15. $i \leftarrow i - 1$

Return to Step 3.

Step 16. Stop.

On receipt of the appropriate commands, discussed in Section VII, the inferential processor generates a particular solution of the form

$$\begin{aligned} 0 &= g_0(\underline{v}) \\ u_1 &= g_1(\underline{v}) \\ u_2 &= g_2(\underline{v}) \\ &\vdots \\ u_q &= g_q(\underline{v}), \end{aligned} \tag{3.58}$$

(where the first equation, as before, is the consistency-condition) by implementing the following algorithm:

Step 1. $g_0 \leftarrow e_{u_1,\ldots,u_q}\phi$

Step 2. Print g_0.

Step 3. $i \leftarrow 1$

Step 4. $g_i \leftarrow e_{u_{i+1},\ldots,u_q}\phi$

Step 5. $g_i \leftarrow g_i/\bar{u}_i$

Step 6. Print g_i.

Step 7. $\phi \leftarrow \phi + (u_i \oplus g_i)$

Step 8. $\phi \leftarrow e_{u_i}\phi$

Step 9. If $i = q$, go to Step 11; otherwise continue.

Step 10. $i \leftarrow i + 1$

Return to Step 4.

Step 11. Stop.

Steps 1 and 2 above produce and print the consistency-condition. Steps 4 through 6 produce and print a solution for u_i in terms of $\underline{v}$, after eliminating the variables u_{i+1} through u_q. Steps 5 and 6 involve operations defined in Section VI. The operation shown in Step 5 is that of logical division; the operation in Step 6 is the production of an irredundant formula (a formula made up entirely of prime implicants, none of which may be dropped without changing the function represented by the formula, i.e., a "locally minimum" formula). Step 7 enforces the condition

$$u_i = g_i \,, \tag{3.59}$$

after which Step 8 eliminates the variable u_i.

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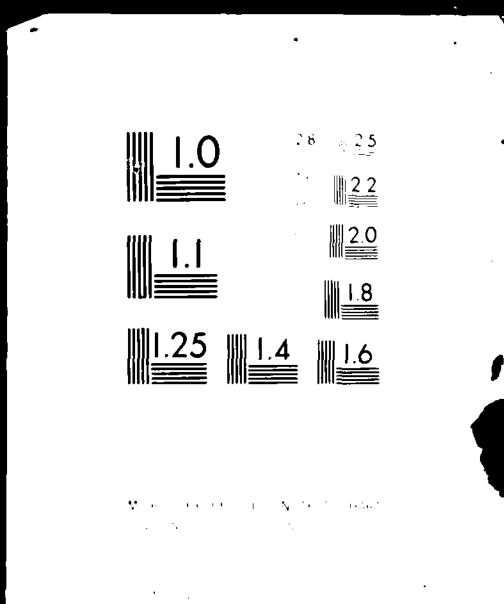

IV. ORGANIZATION OF THE INFERENTIAL PROCESSOR

We present in this section a summary description of the organization and operation of the proposed inferential processor. Section V describes one of its two major components, the minterm-processor; Section VI describes its other major component, the term-processor.

Like a floating-point or FFT processor, the inferential processor is to be a special-purpose adjunct to a general-purpose (host) computer. It appears to the host computer as a manipulator of terms. As illustrated in Figure 4.1, the inferential processor receives its input from the host computer in the form of terms and returns its results to the host computer in the same form. The term, therfore, is the fundamental datum of interest to the user.

The variables from which terms are assembled will be denoted by $x_1, x_2, \ldots, x_n$, the value of n being fixed.

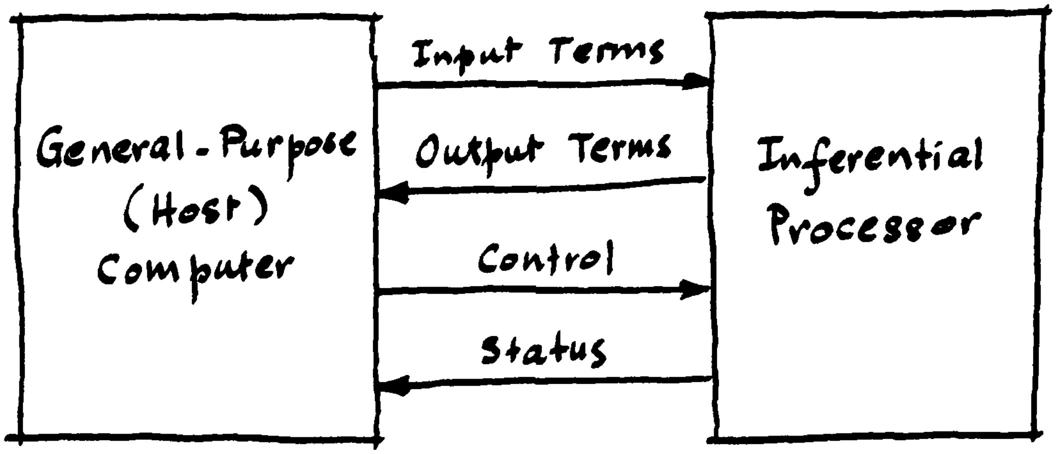

Fig. 4.1. Signal-exchange between host and processor.

Design Considerations

Logical processing entails very long sequences of combinatorial operations. The purpose of the proposed inferential processor is to enable such sequences to be performed rapidly, to provide a marked increase in speed

over that which could be attained in a general-purpose computer. It is generally the case that an increase in speed is achieved only by an increased investment--in parts, dollars, and complexity. We therefore envision two inferential processors; call them Mark I and Mark II.

Mark I would have the organizational and functional features essential to our present conception of inferential processing, achieved with the lowest feasible penalty in cost and complexity but allowing compromises in speed. Mark II, on the other hand, would take advantage of every opportunity to increase its speed that does not exact an exorbitant penalty.

This report is essentially a description of Mark I, a prototype of which could be assembled with a relatively small expenditure of time and money.

It is true of virtually any digital processing task that the greatest speed is achieved if a wired controller (e.g., a PLA tied to a state-register) supervises a wired processor (dedicated registers and logic). A wired controller, however, is difficult to design, takes up a lot of board-space, and is very hard to modify. A wired processor suffers from substantially the same set of disadvantages. Mark I should not, therefore, be an all-wired machine. Its controller should be microprogrammed, employing sequencer-chips (e.g., SN74S482's) to address a microprogram stored in read-only memory. The convenience, economy, and flexibility of microprogrammed control greatly outweigh the penalty in speed which it entails; therefore, microprogramming is recommended also for Mark II.

The best approach to the design of the processor-portion of Mark I is to make use of bit-slice units (e.g., Am2901's) for both registers and logic. This approach allows a change in processor-design to be implemented simply by changing the controller's microprogram. Although typically thought of as a "fast" species of processor, a bit-slice array consumes many more clock-cycles to execute a given register-transfer than would a wired design, whose registers and logic are assembled from dedicated MSI and LSI. The processor in Mark II should therefore, from present indications, be wired.

The foregoing distinction between Mark I and Mark II is based on structure, i.e., on the way hardware is put together. Another distinction is based on function, i.e., on the kinds of operations that can be performed.

Mark I is conceived as a kind of logical calculator, which performs operations of logical analysis under fairly detailed supervision by the user, presumed to be sitting at a terminal monitored by the host computer. The user types commands (to be specified in Sections V and VI of this report) and receives output, with the host-computer functioning as a translator and storage medium. Mark II, however, would operate under stored-program control by the host computer. Experience with Mark I should point to higher-order functions to be incorporated into Mark II, entailing the sequencing of the basic operations discussed in this report.

Principal Components

The inferential processor has two major components, the minterm-processor and the term-processor. Another component, the term-register (labelled TERM), is an important way-station for data. The chief signal-paths connecting these components to eachother and to the host computer are indicated in Figure 4.2.

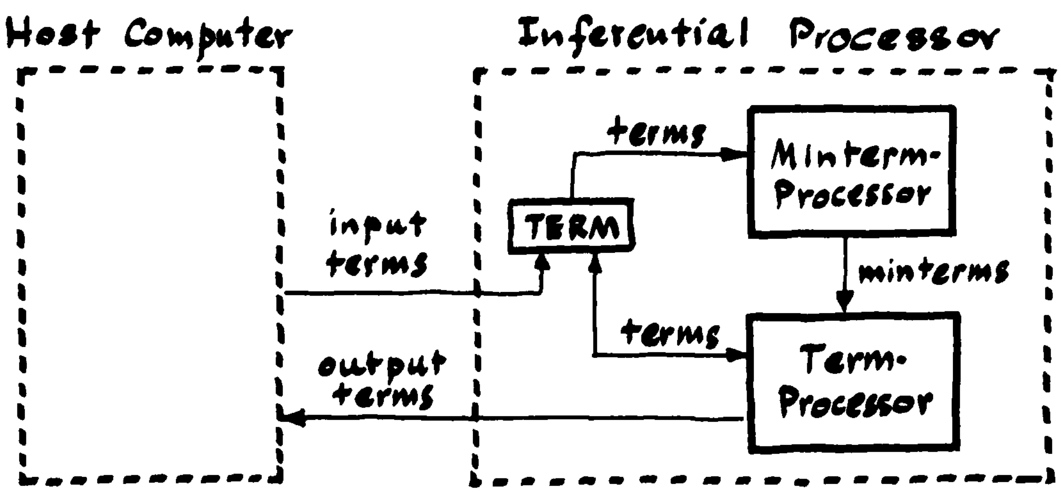

Fig. 4.2. Transfer-paths for terms and minterms.

TERM stores the term currently under consideration by the inferential processor. This term may be supplied by the host computer or by the term-processor.

The minterm-processor accepts terms from the register TERM, building

from them a Boolean function $\phi(x_1,\ldots,x_n)$ using the elementary logical operations AND, OR, NOT, EOR, etc. The operation to be performed at each stage of processing is specified by the host computer. The minterm-processor stores an n-variable Boolean function by recording its 2^n minterm-coefficients; the term received from TERM is first broken down into its minterms, and all operations in the minterm-processor are carried out on minterm-coefficients. The minterm-coefficients of the function ϕ, once assembled by the minterm-processor, are transmitted serially to the term-processor.

The term-processor stores Boolean functions as SOP formulas, i.e, as collections of terms. It receives input terms normally from the minterm-processor (minterms are specialized terms); however, terms may also be received from the host computer, via the register TERM. The term-representation enables the operations of logical inference to be carried out conveniently. The primary operation of the term-processor is that of generating the Blake canonical form (the sum of all the prime implicants) of a Boolean function.

The term-processor makes use of the minterm-processor whenever it is necessary to carry out an operation (complementation, for example) that is not done conveniently in the term-representation; the terms to be worked on by the minterm-processor are transmitted via the register TERM. The term-processor sends terms to the host computer when the latter requests output.

Major Phases of Operation

The work of the inferential processor is done in three major phases:

(1) reduction;
(2) development; and
(3) analysis.

Phase (1), reduction, takes place in the minterm-processor. In this phase, a system of equations and inclusions, transmitted from the host computer in a suitable format, is reduced to a single equation of the form

$$\phi(x_1,\ldots,x_n) = 0 \quad .$$

All functions generated by the inferential processor are assumed to be the left-hand members of equations of the form

$$\text{something} = 0 \;;$$

thus, the task of the minterm-processor is to produce the function ϕ.

Phases (2) and (3)--development and analysis--are carried out in the term-processor. In the development phase, the minterm representation of the function ϕ, produced in the minterm-processor, is transmitted to the term-processor; the term-processor then transforms the ϕ-representation into Blake canonical form.

In phase (3), analysis, the particular deductive processes requested by the host computer are carried out. Such processes might include elimination of variables, generation of conclusions of specialized kinds, solution for a given subset of variables in terms of another subset of variables, and a variety of specialized tasks. Among the latter are the design of multiple-output logic networks, on-line location of logical stuck-type faults, and the determination of keys in relational databases--to consider only logical problems studied by this author. The operations performed by the term-processor during the analysis phase are determined by a sequence of commands transmitted by the host computer; these commands are discussed in Section VI.

Representation of Data

The purpose of the inferential processor is to manipulate Boolean functions. A central problem in design, therefore, is how to represent and store such functions.

A Boolean function may be expressed as the sum of its minterms or, more generally, as an SOP formula, i.e, as the sum of terms which may or may not be minterms. Each of the operations desired in a logical processor is suited either to the minterm-representation or to the term-representation; an operation that is easy to mechanize in one representation is usually difficult or impossible to mechanize in the other. In general, the classical operations of logic (AND, OR, NOT, etc.) are well-adapted to the minterm-representation, whereas the operations useful in logical inference (conversion to Blake canonical form, elimination of variables, etc.) require the term-representation.

Minterm representation. Suppose that $n=3$ and that we are given a function $f(x_1,x_2,x_3)$ represented by the following truth-table:

x_1	x_2	x_3	$f(x_1,x_2,x_3)$
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

(4.1)

We call the entries 0,1,0,1,1,0,0,1 in the function-column of (4.1) the minterm-coefficients of the function f. The function is expressed as follows in minterm canonical form:

$$f = \bar{x}_1\bar{x}_2x_3 + \bar{x}_1x_2x_3 + x_1\bar{x}_2\bar{x}_3 + x_1x_2x_3 \ . \tag{4.2}$$

An n-variable minterm-memory is a $2^n \times 1$ device which stores the sequence of minterm-coefficients of an n-variable Boolean function. A 3-variable minterm-memory representing the function (4.1), for example, would store eight one-bit words, viz.,

0
1
0
1
1
0
0
1

Each address in such a memory corresponds in a natural way to a minterm; thus, address 010 corresponds to the minterm $\bar{x}_1x_2\bar{x}_3$.

Term representation. A minterm-memory is convenient if one wishes to carry out logical operations--such as AND, OR, and NOT--which are performed bit-by-bit on the minterm-coefficients of the operands to yield the minterm-coefficients of the result. Other logical operations on a Boolean function f,

e.g., the production of BCF(f), require that a memory be able to store the terms of an arbitrary SOP formula for the function f. We call such a memory a term-memory.

Let us consider an example. A term-memory would store the SOP formula

$$f = \bar{x}_1 x_3 + x_2 x_3 + x_1 \bar{x}_2 \bar{x}_3 \quad , \tag{4.3}$$

which is equivalent to the formula (4.2), by a sequence of three words, one for each term, as shown in Figure 4.3. Each term, t, in the SOP formula to be stored is encoded in the memory by a word we call a term-representation for t, denoted by R(t). The first address of the sequence of term-representations is indicated by a register we call FIRST, the last by a register we call LAST.

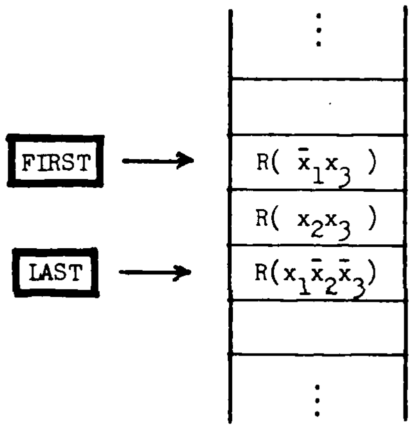

Fig. 4.3. Representation in a term-memory of the SOP formula $\bar{x}_1 x_3 + x_2 x_3 + x_1 \bar{x}_2 \bar{x}_3$.

In order to define the term-representation R(t), it is necessary to examine carefully the nature of a term. A given variable, x_i, can be either present or absent in a term. If it is present, it can appear either complemented or uncomplemented. Thus, every term t on n variables is equivalent to (i.e., denotes the same Boolean function as) an expression of the form

$$t = \alpha_1(t)\alpha_2(t)\cdots\alpha_n(t) \quad ,$$

where $\alpha_i(t) \in \{\bar{x}_i, x_i, 1\}$. Since a variable can be present in a term in one of three ways, we express the relation of x_i to a term t (for $i = 1,2,\ldots,n$) by two variables; we call them the <u>explicit</u> variable, $E_i(t)$, and the <u>polar</u> variable, $P_i(t)$. Values are assigned to $E_i(t)$ and $P_i(t)$ according to the scheme shown in Figure 4.4. The explicit variable has the value 1 if and only if x_i is explicit in t; the polar variable has the value 1 if and only if x_i is explicit in t and also appears uncomplemented.

$\alpha_i(t)$	$E_i(t)$	$P_i(t)$
$\bar{x}_i$	1	0
x_i	1	1
1	0	0

Figure 4.4. Definition of explicit
and polar variables.

For convenience in processing, the E-bits and P-bits will be separated into two fields, labelled E and P, in each word of the term-memory. The symbolic memory-contents shown in Figure 4.3 therefore take the specific form shown in Figure 4.5.

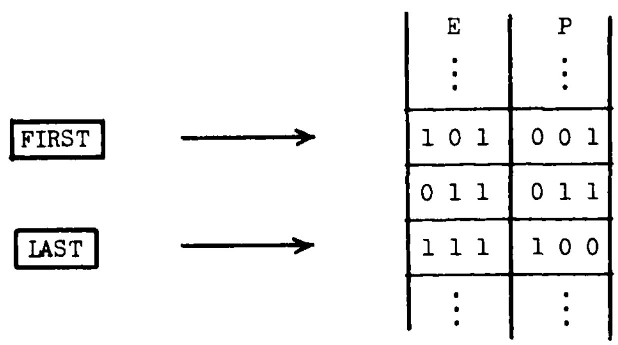

Fig. 4.5. E and P fields of a term-memory
storing $\bar{x}_1x_3 + x_2x_3 + x_1\bar{x}_2\bar{x}_3$.

It should be noted that the Boolean function 1 is a term, namely that term in which no variable is explicit; thus R(t) = all 0's. The Boolean function 0 is represented in a term-memory as an empty collection of terms. Such a collection is indicated in case LAST = FIRST - 1 (the relation hold-

ing between the pointers FIRST and LAST before the first word is loaded).

Some variation of the term-representation discussed above will almost inevitably be chosen in a special-purpose machine designed for logical processing. The earliest documentation of such a scheme available to the author is that given by Florine [19], whose logical processor is the subject of a full-length text [20]. The same scheme has been used by Svoboda [55] (who calls it "triadic" and devotes much attention to base-3 calculations; see the text by Svoboda and White [58] for details), by Gerace, et al. [24] and by Gómez-González [26].

Memory Requirements

The number of words in a minterm memory is precisely 2^n, where n is the number of variables being processed. The number of words appropriate to a term-memory, however, is not so easily decided. There are 3^n possible terms on n variables (this following from our earlier observation that a variable can be present in a term in one of three ways). If $n = 15$, for example, the number of minterms is 32,768--whereas the number of terms is 14,348,907. It is difficult to decide what fraction of this very large population of possible terms one is likely to want to store.

Some guidance in choosing a suitable size for a term-memory is provided by the fact that the primary task of the term-processor is to manipulate functions expressed in Blake canonical form. We may safely concentrate, therefore, on storing a particular subset of the full set of 3^n possible implicants of a function f, namely, the prime implicants of f.

For n greater than 5, the number of prime implicants a function can possess exceeds the number of minterms. If $n = 15$, as noted earlier, there are 32,768 minterms; it is known, however, that there are functions of 15 variables (probably not a large fraction of the total population of 15-variable functions) whose prime-implicant count lies somewhere between the bounds of 756,756 and 3,075,072 (see Section VI). The number of variables that can be processed by an inferential processor is clearly limited by its ability to store prime implicants. This question is discussed at greater length in Section VI, where it is conjectured that a 64K term-capacity would suffice if $n = 15$ (overflow occurring in very rare instances).

V. MINTERM-PROCESSOR

The minterm-processor performs three principal tasks:

1) it accepts a sequence $t_1, t_2, \ldots, t_k$ of terms (either from the host computer or from the term-processor) and stores the corresponding Boolean function $\sum_{i=1}^{k} t_i$;

2) it carries out logical operations on the Boolean functions it stores; and

3) it transmits Boolean functions to the term-processor.

General Description

The principal components of the minterm-processor are shown in Figure 5.1. The central component is an array M(0), M(1), M(2), M(3) of minterm-memories, each of which is a $2^n \times 1$ random-access memory (RAM). These memories constitute a four-word stack, each word in the stack storing the 2^n minterm-coefficients of a Boolean function. If n has the value 3, for example, then the function whose truth-table is

x_1	x_2	x_3	$f(x_1, x_2, x_3)$
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

would be stored in a minterm-memory as the 2^3-bit word 01110011.

Words are stored "vertically in the minterm-memories, with the stack-counter (STK) functioning as a word-pointer and the minterm-counter (MIN) functioning as a bit-pointer. STK determines which of the four $2^n \times 1$ RAM's will receive data. MIN addresses the RAM's in parallel; each RAM-address (i.e., each n-bit pattern MIN is capable of generating) corresponds as shown in Figure 5.2 to a minterm of the variables $x_1, x_2, \ldots, x_n$.

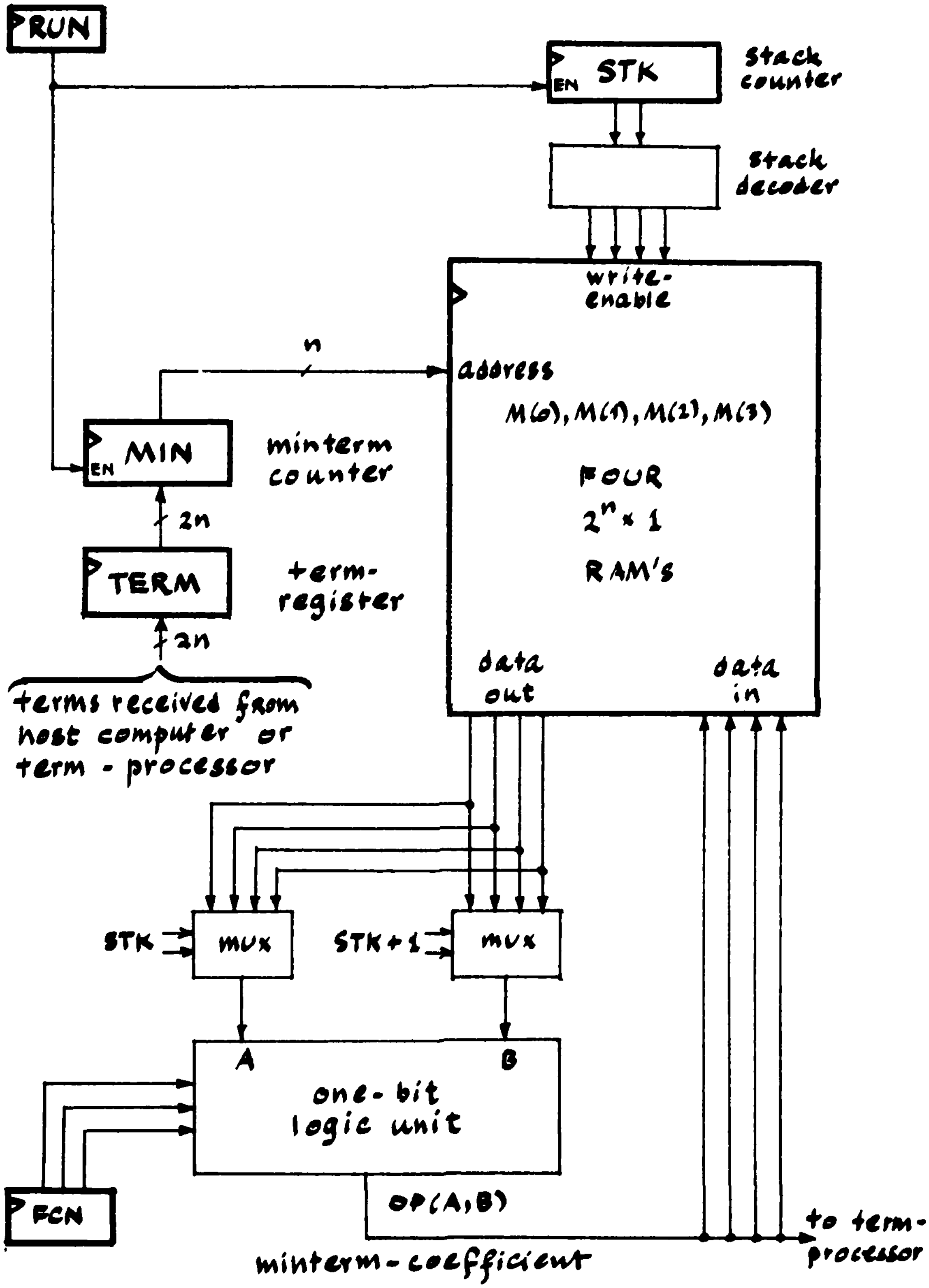

Fig. 5.1. Principal components of the minterm-processor.

RAM address	minterm represented
$0 \cdots 00$	$\bar{x}_1 \cdots \bar{x}_{n-1}\bar{x}_n$
$0 \cdots 01$	$\bar{x}_1 \cdots \bar{x}_{n-1}x_n$
$0 \cdots 10$	$\bar{x}_1 \cdots x_{n-1}\bar{x}_n$
$\vdots$	$\vdots$
$1 \cdots 11$	$x_1 \cdots x_{n-1}x_n$

Fig. 5.2. Correspondence between RAM-addresses and x-minterms.

The count-cycle of MIN is controlled by the contents of the term-register, TERM; MIN generates those addresses which correspond to minterms of the term stored in TERM, skipping over the addresses which do not.

When RUN is set, each clock-cycle causes the transfer

$$M(STK,MIN) \leftarrow OP(M(STK,MIN),\ M(STK+1,MIN))$$

to be carried out, where M(I,J) denotes bit J of M(I) and where OP is a combinational operation carried out by the one-bit logic-unit shown in Figure 5.1.

Registers

To present a more detailed description of the functioning of the minterm-processor, it is necessary to discuss its principal registers, viz., FCN, STK, TERM, MIN, and RUN.

FCN. The logic-unit shown in Figure 5.1 carries out a combinational operation OP(A,B), where OP $\in$ {ZERO, ONE, TRUE, NOT, AND, OR, EOR, LE}. These operations are defined as follows:

$$\begin{aligned} ZERO(A,B) &= 0 \\ ONE(A,B) &= 1 \\ TRUE(A,B) &= A \\ NOT(A,B) &= \bar{A} \\ AND(A,B) &= AB \\ OR(A,B) &= A+B \\ EOR(A,B) &= A \oplus B \\ LE(A,B) &= A\bar{B} \quad . \end{aligned}$$

The only one of the foregoing mnemonics whose origin is not obvious is "LE". The operation LE is read "less than or equal"; it derives from the property that $a \leqslant b$ if and only if the condition $a\bar{b} = 0$ is satisfied.

The register FCN stores a three-bit code which determines which of the eight operations defined above is carried out. We shall denote the codes by the names ZERO, ONE,...,LE, their numerical values being unimportant for the present discussion.

STK. The stack-counter, STK, is a modulo-4 up-down counter. Its use will be clarified in subsequent discussion.

TERM. The register TERM stores the 2n-bit representation $R(t)$ of a term t on n variables. As discussed in Section IV, the leftmost n bits of $R(t)$ constitute the "explicit" field, $E(t)$, and the rightmost n bits constitute the "polar" field, $P(t)$. Suppose that $n = 5$, for example, and that $t = x_2\bar{x}_3x_5$. Then $E(t)$ = 01101 and and $P(t)$ = 01001, whence t would be stored in TERM as the ten-bit pattern $R(t)$ = 0110101001.

TERM receives data either from the host computer or from the term-processor. The most convenient format for specifying the transfer of a term from the host computer to TERM depends on the language used to program the host computer. We assume provisionally that the ordinary mathematical notation for a term t, which we denote by (t), may be used to evoke such a transfer. Thus the statement

$$x_2\bar{x}_3x_5$$

is assumed to transfer $R(x_2\bar{x}_3x_5)$ to the register TERM. The statement

$$1$$

transfers $R(1)$, i.e., 2n zeros, to TERM.

MIN. Each of the four $2^n \times 1$ RAM's $M(0)$, $M(1)$, $M(2)$, and $M(3)$ stores an n-variable Boolean function. The minterm-counter, MIN, is the memory-address register for these RAM's; each address corresponds to a minterm according to the scheme shown in Figure 5.2.

The task of the minterm-counter is to cycle through just those addresses which correspond to minterms of the term t stored in TERM. A q-literal term on n variables has 2^{n-q} minterms; thus, a complete cycle of MIN consists of the

generation of 2^{n-q} addresses. If t is a minterm, i.e., if $q = n$, then a complete cycle of MIN consists of just one address. At the other extreme, if t is the term 1 (i.e., if $q = 0$), then a complete cycle of MIN consists of all 2^n possible addresses.

MIN is a synchronous counter, designed to advance from one of the desired addresses directly to another such address, skipping over addresses that do not correspond to minterms of t. Thus, 2^{n-q} clock-periods are required for a cycle of MIN.

Reverting to an earlier example, suppose that $n = 5$ and that $t = x_2\bar{x}_3x_5$. Then E(t) = 01101 and P(t) = 01001. Setting RUN causes P(t) to be loaded as the initial contents of MIN, after which the n-q bits labelled 0 in E(t), which are loaded into MIN initially as 0's, are counted through all combinations. The resulting sequence of addresses produced by MIN is shown below:

01001
01011
11001
11011 .

Thus, the term $x_2\bar{x}_3x_5$ causes all addresses of the form X10X1 to be generated.

The detailed design of the minterm-counter is discussed in [[illegible]].

<u>RUN</u>. When the flip-flop RUN is set, a cycle of the minterm-counter is initiated. RUN remains set while MIN generates addresses, and is cleared by MIN when the cycle is complete. When RUN is set, the stack-decoder is enabled; thus, the data produced by the logic-unit are written into the addresses generated during a cycle of MIN.

Commands

The minterm-processor responds to three classes of commands supplied by the host computer, viz., ENTER, (t), and OP. The command ENTER prepares the minterm-processor to receive a sequence of terms. (t) denotes the customary mathematical notation for any of the 3^n possible terms on n variables. OP denotes any of the eight operations ZERO, ONE, TRUE, NOT, AND, OR, EOR, and LE constituting the repertoire of the one-bit logic unit.

The effect of these commands on the contents of the minterm-memory is summarized below.

$$\begin{array}{rl} \text{ENTER:} & STK \leftarrow STK + 1 \\ & M(STK) \leftarrow 0 \\[1ex] (t): & M(STK) \leftarrow M(STK) + R(t) \quad \text{(logical sum)} \\[1ex] \text{OP:} & STK \leftarrow STK - 1 \\ & M(STK) \leftarrow OP(M(STK),\ M(STK+1)) \end{array}$$

To implement the foregoing memory-transformations, the microprogram controlling the inferential processor evokes transfers as follows on the registers STK, TERM, FCN, and RUN:

$$\begin{array}{rlll} \text{ENTER:} & STK \leftarrow STK+1, & TERM \leftarrow R(1), & FCN \leftarrow ZERO \\ & RUN \leftarrow 1 & & \\ & \text{(wait until RUN clears)} & & \\[1ex] (t): & FCN \leftarrow ONE, & TERM \leftarrow R(t) & \\ & RUN \leftarrow 1 & & \\ & \text{(wait until RUN clears)} & & \\[1ex] \text{OP:} & STK \leftarrow STK-1, & TERM \leftarrow R(1), & FCN \leftarrow OP \\ & RUN \leftarrow 1 & & \\ & \text{(wait until RUN clears)} & & \end{array}$$

<u>Entering an SOP formula</u>. Suppose $n = 3$. To enter the SOP formula $f = x_2 + x_1\bar{x}_3$, the host computer supplies the sequence

$$\begin{array}{l} \text{ENTER} \\ x_2 \\ x_1\bar{x}_3 \end{array}$$

of commands to the inferential processor.

Entering a non-SOP formula. The term-format for entry of data into the inferential processor makes SOP formulas particularly convenient to enter. Non-SOP formulas, however, are entered with little difficulty. To enter the formula

$$\overline{(x_1 + \bar{x}_2x_3)x_4 \oplus \bar{x}_1x_3} + x_1\bar{x}_2x_4 \quad ,$$

for example, the host computer supplies the sequence

ENTER
x_1
$\bar{x}_2x_3$
ENTER
x_4
AND
ENTER
$\bar{x}_1x_3$
EOR
NOT
ENTER
$x_1\bar{x}_2x_4$
OR

Entering a system of equations. Consider the system

$$g_1 = h_1$$
$$g_2 \leqslant h_2$$
$$g_3 = h_3$$

of Boolean equations and implications, where the g's and h's are Boolean formulas. This system is equivalent to the single equation

$$f = 0 \ ,$$

where the function f is defined by the formula

$$f = (g_1 \oplus h_1) + g_2\bar{h}_2 + (g_3 \oplus h_3) \ .$$

To enter the function f, the host computer transmits the sequence

(enter g_1)
(enter h_1)
EOR
(enter g_2)
(enter h_2)
LE
OR
(enter g_3)
(enter h_3)
EOR
OR .

As a more detailed example, consider the system

$$\bar{x}_1 x_2 \leq x_2 + \bar{x}_1 \bar{x}_3$$
$$x_1 x_2 \bar{x}_3 + \bar{x}_2 x_3 = x_1 + x_2 x_3 \quad .$$

To enter this system , the host computer transmits the sequence

ENTER
$\bar{x}_1 x_2$
ENTER
x_2
$\bar{x}_1 \bar{x}_3$
LE
ENTER
$x_1 x_2 \bar{x}_3$
$\bar{x}_2 x_3$
ENTER
x_1
$x_2 x_3$
EOR
OR .

Walk-through of register contents. The effect of the commands ENTER, (t), and OP is perhaps best understood by contemplating the sequence of register and memory-values as a system of equations and implications is entered into the minterm-processor. Figure 5.3 shows such a walk-through as the system

$$\begin{aligned} x_1\bar{x}_2 + \bar{x}_1x_3 &= x_2\bar{x}_3 \\ x_1x_2 &= 0 \\ 1 &= \bar{x}_1 + x_3 \end{aligned} \tag{5.1}$$

is entered into the minterm-processor. Each row in Figure 5.3 corresponds to a command, which is listed in the leftmost column. Succeeding columns specify register-contents <u>after</u> execution of the command. We assume that the initial value of STK is 0. To conserve space in Figure 5.3, we define the following subfunctions:

$$\begin{aligned} g_1 &= x_1\bar{x}_2 + \bar{x}_1x_3 \\ h_1 &= x_2\bar{x}_3 \\ g_2 &= x_1x_2 \\ h_3 &= \bar{x}_1 + x_3 \quad . \end{aligned}$$

Employing these subfunctions, the system (5.1) is equivalent to the single equation

$$(g_1 \oplus h_1) + g_2 + \bar{h}_3 = 0. \tag{5.2}$$

After execution of the commands in the first column of Figure 5.3, the function stored in M(STK) is that displayed on the left-hand side of equation (5.2).

command	TERM	FCN	STK	M(STK)	M(STK-1)	M(STK-2)	M(STK-3)
ENTER	000000	ZERO	1	0	–	–	–
$x_1\bar{x}_2$	110100	ONE	1	$x_1\bar{x}_2$	–	–	–
$\bar{x}_1x_3$	101001	ONE	1	g_1	–	–	–
ENTER	000000	ZERO	2	0	g_1	–	–
$x_2\bar{x}_3$	011010	ONE	2	h_1	g_1	–	–
EOR	000000	EOR	1	$g_1 \oplus h_1$	–	–	h_1
ENTER	000000	ZERO	2	0	$g_1 \oplus h_1$	–	–
x_1x_2	110110	ONE	2	g_2	$g_1 \oplus h_1$	–	–
ENTER	000000	ZERO	3	0	g_2	$g_1 \oplus h_1$	–
EOR	000000	EOR	2	g_2	$g_1 \oplus h_1$	–	0
OR	000000	OR	1	$g_2 + (g_1 \oplus h_1)$	–	0	g_2
ENTER	000000	ZERO	2	0	$g_2 + (g_1 \oplus h_1)$	–	0
1	000000	ONE	2	1	$g_2 + (g_1 \oplus h_1)$	–	0
ENTER	000000	ZERO	3	0	1	$g_2 + (g_1 \oplus h_1)$	–
$\bar{x}_1$	100000	ONE	3	$\bar{x}_1$	1	$g_2 + (g_1 \oplus h_1)$	–
x_3	001001	ONE	3	h_3	1	$g_2 + (g_1 \oplus h_1)$	–
EOR	000000	EOR	2	$\bar{h}_3$	$g_2 + (g_1 \oplus h_1)$	–	h_3
OR	000000	OR	1	$\bar{h}_3 + g_2 + (g_1 \oplus h_1)$	–	h_3	$\bar{h}_3$

Fig. 5.3. Evolution of register-contents as the system (5.1) is entered.

VI. TERM-PROCESSOR

The task of the term-processor is to store and process Boolean functions expressed as SOP formulas. The design of the term-processor, unlike that of the minterm-processor, has been completed only at the level of register-transfers, detailed design not being possible within the time allocated for this project. The discussion in this section focuses on the array of memories in the term-processor, with only occasional reference to the associated logic. A relatively complete set of commands has been established; these enable the operations of Boolean analysis to be carried out.

The logic called for in connection with the register-transfers we specify may be implemented either with dedicated IC's (gates, ROM's, PLA's) or by bit-slice units (Am2901's, for example). For a feasibility unit, it would be preferable to seek the economy afforded by bit-slices; for practical implementation, the speed of dedicated IC's would be essential.

Term-Memories

The central component of the term-processor (indicated in Figure 6.1) is an array T(0), T(1), T(2), T(3) of $2^m \times 2n$ term-memories, arranged in the form of a stack. Each term-memory stores the terms of a single Boolean function.

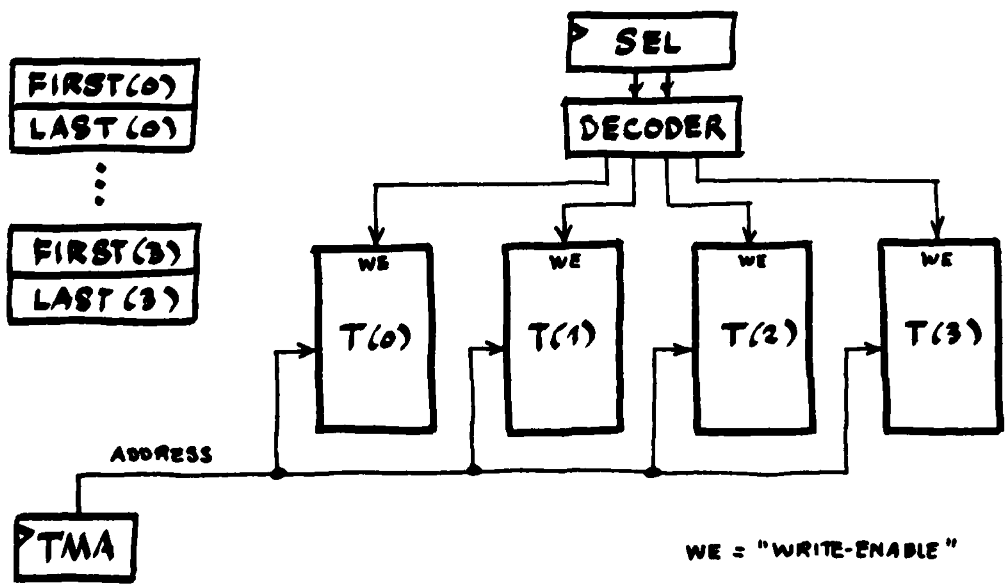

Fig. 6.1. Term-memory array.

The array of term-memories is similar to the array of minterm-memories in that it comprises four units, each of which stores a single Boolean function. The method by which functions are represented in the term-memories is radically different, however, from that by which functions are represented in the minterm-memories. Each of the 2^n words in a minterm-memory stores a one-bit minterm-coefficient (the minterm associated with the coefficient is determined by the address at which the coefficient is stored). Each word in a term-memory, on the other hand, is capable of storing the 2n-bit representation, R(t), of a term t; the address at which R(t) is stored has no relation to the term t.

The terms of an SOP formula for a Boolean function are stored in term-memory T(i) in a contiguous file. The address of the first word in the file is stored in a register labelled FIRST(i); the address of the last word is stored in a register labelled LAST(i). The term-memory under discussion is typically T(SEL), the memory pointed to by the register SEL. The associated registers FIRST(SEL) and LAST(SEL) will usually be called simply FIRST and LAST. If a term is to be deleted from the file (as is frequently required during processing), the word stored at FIRST is put in its place and FIRST is incremented. If a term is to be added to the file, it is placed immediately after the word stored at LAST, whereupon LAST is incremented. Thus, the file "creeps" cyclicly around the term-memory during processing.

Generation and Storage of Prime Implicants

Given a logical database of the form $f(x_1,\ldots,x_n) = 0$, the operations of Boolean analysis are readily mechanized if the function f is expressed in Blake canonical form. For practical values of n, however, the number of terms in BCF(f) may become quite large and the process of generating BCF(f) may be very time-consuming. The time and space problems associated with generating and storing BCF(f) are in fact the principal reasons for constructing a special-purpose logical processor.

As noted in Section III, there are a number of approaches to the generation of the Blake canonical form. Each of these approaches, if applied naively, consumes vast quantities of time and storage-space for practical values of n. A study of the extensive literature on the generation of prime implicants

reveals one algorithm that grapples seriously with the problem of conserving space and keeping computation-time to a minimum. It is significant that that algorithm was devised for implementation on a "logical" computer--a special-purpose machine called TOPI [24], designed for the synthesis and analysis of Boolean functions. The TOPI-algorithm will be mechanized in the proposed inferential processor.

The documentation presently available concerning TOPI (which was built in Italy) presents only a brief sketch of the algorithm for generating prime implicants. Considerable effort was devoted in this project to developing detailed flowcharts specifying the algorithm. This work, though not sufficiently complete to report here, has progressed far enough to verify the feasibility of the TOPI approach.

In most phases of operation of the term-processor, the term-memories store BCF-representations. The TOPI procedure conserves memory-space carefully during the generation of prime implicants; therefore the number, 2^m, of words in the term-memories may be chosen to accomodate the largest number of prime implicants expected for the given value of n (no allowance need be made for the wasted space and the repetitions associated with most of the published procedures for generating prime implicants).

Let M(n) denote the maximum number of prime implicants that a function of n variables can possess. The problem of determining M(n) as a function of n is under active study by a number of investigators at the present time. A lower bound,

$$\max_{i,j}\left[\frac{n!}{i!\ j!\ (n-i-j)!}\right] \leq M(n) \quad ,$$

was given by Dunham and Fridshal [18]. An upper bound on M(n),

$$M(n) \leq \binom{n}{g(n)} \cdot 2^{g(n)} \quad ,$$

where $g(n) = \left\lfloor \frac{2n+1}{3} \right\rfloor$, was given by Chandra and Markowsky [14] (see Igarashi [28] for a discussion of the current state of research on the determination of M(n)).

A tabulation of the foregoing bounds is given in Table 6.1 for values of n from 3 to 16.

n	Lower Bound on M(n)	Upper Bound on M(n)
3	6	12
4	12	32
5	30	80
6	90	240
7	210	672
8	560	1,792
9	1,680	5,376
10	4,200	15,360
11	11,550	46,464
12	34,650	126,720
13	90,090	366,080
14	252,252	1,025,024
15	756,756	3,075,072
16	2,018,016	8,945,664

Table 6.1. Lower and upper bounds on the maximum number of prime implicants that an n-variable Boolean function can possess.

The numbers in Table 6.1 seem to indicate that the term-memories must be very large if n exceeds ten or twelve. It is the author's belief, however, that it is a very rare function whose prime-implicant count approaches even the lower bound cited above. Rather than attempting to construct term-memories capable of storing M(n) words, whatever the estimate of M(n), it would seem preferable to provide K(n) words of term-storage, where K(n) is a number such that 99.9% (or some other suitable percentage) of all functions of n variables have fewer than K(n) prime implicants. If the capacity of a term-memory were exceeded, the user could attempt to reduce the number of variables, partition the problem in some way, or chain the term-memories. A serious difficulty with this suggestion, however, is the need to determine K(n) by experiment. For

practical values of n, the population 2^{2^n} of functions of n variables is so large that it is difficult to imagine how one might produce a "representative" sample of functions to test. There are, for example, about 2×10^{308} Boolean functions of 10 variables.

The lack of knowledge concerning the distribution of prime-implicant counts among Boolean functions need not deter one from constructing an inferential processor. One should simply provide as much term-memory as is economically feasible, using the bounds on M(n) as rough indicators of "safe" values. For values of n exceeding 12, the author's intuition is that an extremely small fraction of Boolean functions would possess more than (lower bound)/10 prime implicants. Thus, term-memories of 64K capacity would appear to overflow very seldom if $n = 15$.

Term-Operations

The term-processor responds to the following commands:

BCF
(t)
NTERM
OUT
TEST1
PUSH
POP
LDM
LDT
ADD
COMP
STO
RCL
DIV
EONE
EZERO
PROJ
IRR

The operations inaugurated by these commands are explained in the following paragraphs. The commands BCF, ADD, COMP, DIV, EONE, EZERO, PROJ, and IRR cause changes in the nature or form of the Boolean function stored in T(SEL). The result of each of these commands except IRR is a function stored

in T(SEL) in Blake canonical form; IRR produces a function that is typically not in Blake canonical form.

The commands tabulated above appear at this stage of development of the inferential processor to be a convenient minimal set for the purposes of Boolean analysis. Higher-order commands having more specialized application, which evoke sequences of commands taken from the foregoing set, are discussed in Section VII, along with the applications for which they have been devised.

BCF. It is necessary in most phases of operation of the term-processor that Boolean functions be represented in Blake canonical form. The command

BCF

evokes a sequence of term-substitutions in T(SEL) whose effect is to carry out the transfer

$$T(SEL) \leftarrow BCF(T(SEL)) \quad .$$

The BCF-operation does not change the function stored in T(SEL); instead, it causes that function to be represented by the set of all of its prime implicants. If the function stored in T(SEL) is already in Blake canonical form, then the term-processor will respond to the command BCF by simply scanning the terms stored in T(SEL), without modifying them.

Although available to the user as a command to the inferential processor, the BCF-operation is most frequently evoked as part of other term-operations, to be discussed in the sequel.

(t) and NTERM. The operations (t) and NTERM affect the TERM-register, and do not cause modifications in the term-processor. They are executed within sequences of term-operations, however, so that they are most logically discussed along with those operations.

The notation (t) refers to the ordinary mathematical representation for a term t. The command

(t)

evokes the transfer

$$\text{TERM} \leftarrow R(t) \ ,$$

i.e., it loads the term-representation for t into TERM. Recall that one or more commands of the form (t) may be used after the command ENTER, in which case the command (t) not only loads R(t) into TERM, but also adds t logically to the function stored in the minterm-memory M(STK).

The command

NTERM

changes the polarity of each literal present in the terms stored in the TERM register, implementing the transfer

$$P(\text{TERM}) \leftarrow E(\text{TERM}) \cdot \overline{P(\text{TERM})} \ .$$

If TERM stores the term $x_2\bar{x}_4x_5$, for example, then TERM stores $\bar{x}_2x_4\bar{x}_5$ after execution of NTERM.

<u>OUT</u>. The command

OUT

causes each term stored in T(SEL) to be transferred to the host computer, for display to the user as an SOP formula. The precise display-format will depend on the host computer and the terminal.

<u>TEST1</u>. The command

TEST1

tells the user whether or not T(SEL) is storing the function 1. If the first word stored in T(SEL) is R(1), TEST1 causes YES to be displayed to the user; otherwise, TEST1 causes NO to be displayed. TEST1 should be employed only if the function stored in T(SEL) is in Blake canonical form, in which case the function 1 is represented as the single term R(1), stored at location FIRST(SEL). R(1), it should be recalled, is a word consisting of 2n zeros.

PUSH and POP. The term-memories, as noted earlier, are organized as a four-word stack. The commands PUSH and POP implement the corresponding stack-operations. In particular, the command

PUSH

evokes the sequence

$$\begin{aligned} \mathrm{SEL} &\leftarrow \mathrm{SEL} + 1 \\ \mathrm{T(SEL)} &\leftarrow \mathrm{T(SEL-1)} \ , \end{aligned}$$

of transfers, whereas the command

POP

evokes the transfer

$$\mathrm{SEL} \leftarrow \mathrm{SEL} - 1 \quad .$$

LDM and LDT. The command

LDM

moves a Boolean function from the term-processor to the minterm-processor, effecting the overall transfer

$$\mathrm{M(STK+1)} \leftarrow \mathrm{T(SEL)} \quad .$$

In more detail, LDM evokes the following processing steps:

Step 1. STK $\leftarrow$ STK + 1
Step 2. M(STK) $\leftarrow$ 0
Step 3. TMA $\leftarrow$ FIRST(SEL)
Step 4. TERM $\leftarrow$ T(SEL,TMA)
Step 5. M(STK) $\leftarrow$ M(STK) + TERM
Step 6. If TMA = LAST(SEL), exit LDM. Otherwise, continue.
Step 7. TMA $\leftarrow$ TMA + 1
Step 8. Go to Step 4.

The command

LDT

is essentially the inverse of LDM; that is, LDT moves a Boolean function from the minterm-processor to the term-processor, depositing it in Blake canonical form. Thus LDT effects the sequence

PUSH
T(SEL) $\leftarrow$ M(STK)
BCF .

In more detail, LDT evokes the following sequence of operations:

Step 1. PUSH

Step 2. FIRST $\leftarrow$ 0
LAST $\leftarrow$ 0

Step 3. MIN   0

Step 4. If M(MIN) = 0, go to Step 7; if M(MIN) = 1, continue.

Step 5. E(LAST) $\leftarrow$ 1's
P(LAST) $\leftarrow$ MIN

Step 6. LAST $\leftarrow$ LAST + 1

Step 7. If MIN = 2^n-1, go to Step 9; otherwise, continue.

Step 8. MIN $\leftarrow$ MIN + 1

Step 9. BCF

Step 10. Exit LDT.

FIRST and LAST in the foregoing steps refer to FIRST(SEL) and LAST(SEL), respectively.

<u>ADD</u>. The command

ADD

adds the term stored in TERM to the function stored in T(SEL), leaving the

result in Blake canonical form. Thus, ADD effects the sequence

$$T(SEL) \leftarrow \underset{BCF}{T(SEL) + TERM} \;.$$

COMP. The command

COMP

complements the function stored in T(SEL), leaving the result in Blake canonical form. COMP evokes the sequence

LDM
NOT
LDT
POP
BCF .

STO and RCL. The host computer supplies space for the term-processor to store Boolean functions in term-format. The command

STO (name)

transfers a Boolean function from the term-processor to a file, entitled (name), which is created and maintained by the host computer. The command

RCL (name)

transfers the contents of (name) to the term processor. In detail:

STO (name): (name) ← T(SEL)

RCL (name): T(SEL) ← (name) .

DIV. Let f be a Boolean function and let t be a term. We define f/t to be the function derived from f by enforcing the constraint $t=1$. If $t=\bar{x}_3$, for example, then f/t is the function derived from f by setting $x_3=0$. If $t=\bar{x}_3x_4$, then f/t is the function derived from f by setting $x_3 = 0$ and $x_4=1$. Suppose $f = x_1\bar{x}_3 + \bar{x}_1x_2x_4 + \bar{x}_1x_3\bar{x}_5 + \bar{x}_2\bar{x}_4$. Then $f/\bar{x}_3 = x_1\cdot 1 + \bar{x}_1x_2x_4 + \bar{x}_1 \cdot 0 \cdot \bar{x}_5 + \bar{x}_2\bar{x}_4 = x_1 + x_2x_4 + \bar{x}_2\bar{x}_4$. Also, $f/\bar{x}_3x_4 = (f/\bar{x}_3)/x_4 = x_1 + x_2\cdot 1 + \bar{x}_2\cdot 0$

$= x_1 + x_2$. The command

DIV

effects the following sequence:

PUSH

$T(SEL) \leftarrow T(SEL)/TERM$

BCF .

In more detail, DIV evokes the following subroutine in the term-processor:

Step 1. PUSH

Step 2. TMA $\leftarrow$ FIRST

Step 3. If T(TMA)/TERM = 0, go to Step 5; otherwise, continue.

Step 4. T(TMA) $\leftarrow$ T(TMA)/TERM
Go to Step 7.

Step 5. T(TMA) $\leftarrow$ T(FIRST)

Step 6. FIRST $\leftarrow$ FIRST + 1

Step 7. If TMA $\neq$ LAST, continue; if TMA = LAST, go to Step 9.

Step 8. TMA $\leftarrow$ TMA + 1
Go to Step 3.

Step 9. BCF
Exit DIV.

Suppose a Boolean function f is represented in a term-memory by the sequence $p_1, p_2, \ldots, p_k$ of terms, which have the property that $f = \sum_{j=1}^{k} p_j$. Then the sequence of steps above generates $q = f/t$ by producing p_j/t for $j = 1,2, \ldots, k$. The logic required to produce $q_j = p_j/t$ consists of n units operating in parallel. The i-th unit receives $R(p_j^i)$ and $R(t^i)$ as inputs and produces $R(q^i)$; in particular, unit i generates the functions

$$E_q = E_p E_t$$

$$P_q = P_p \overline{E}_t$$

$$Z = E_p E_t (P_p \oplus P_t) ,$$

the i-superscripts and j-subscripts having been suppressed. If any of the outputs Z^1, $Z^2, \ldots, Z^n$ has the value 1, then $p_i/t = 0$. Thus, Step 3 in the subroutine listed above tests ZERO = $\sum_{i=1}^{n} Z^i$.

EONE and EZERO. The elimination-operators E and e were discussed in Section III. These operators enable a subset of the variables $x_1, \ldots, x_n$ to be removed from consideration in processes of logical inference. Let f be a Boolean function and let t be a term. If f is expressed in Blake canonical form, then the functions $e_t f$ and $E_t f$ are readily determined by use of the techniques described in Section III; we refer to these functions as the zero-eliminant and one-eliminant, respectively, of f with respect to t.

The command

EONE

generates the 1-eliminant of T(SEL) with respect to the variables explicit in TERM. Let f be the function stored in T(SEL). Then f is given by the summation $\sum_{j=1}^{k} p_j$, where $p_1, \ldots, p_k$ are the terms stored in T(SEL). The identity $E_t \sum_{j=1}^{k} p_j = \sum_{j=1}^{k} E_t p_j$ enables $E_t f$ to be generated by scanning the contents of T(SEL): the procedure in detail is listed below.

Step 1. PUSH

Step 2. TMA $\leftarrow$ FIRST

Step 3. T(TMA) $\leftarrow$ E_tT(TMA)

Step 4. If T(TMA) = 1, go to Step 7; otherwise, continue.

Step 5. If TMA = LAST, go to Setp 8; otherwise, continue.

Step 6. TMA $\leftarrow$ TMA + 1
Go to Step 3.

Step 7. T(FIRST) $\leftarrow$ T(TMA)
LAST $\leftarrow$ FIRST
Go to Step 9.

Step 8. BCF

Step 9. Exit EONE.

Step 3 of the foregoing procedure requires logic to generate the term $q = E_t p$, given the terms t and p. A parallel array of n logic-elements is required; a one-bit slice of this array is defined by the equations

$$E(q) = E(p) \cdot \bar{E}(t)$$

$$P(q) = P(p) \cdot \bar{E}(t) \quad .$$

The command

EZERO

generates the 0-eliminant of T(SEL) with respect to the variables explicit in TERM. This command will be executed properly only if T(SEL) is in Blake canonical form, in which case the 0-eliminant is generated by selective deletion of terms from T(SEL) (cf. Section III). The procedure for generating the 0-eliminant of T(SEL) with respect to the variables explicit in TERM is detailed below:

Step 1. PUSH

Step 2. TMA $\leftarrow$ FIRST

Step 3. If E(T(TMA)) $\cdot$ E(TERM) = all 0's, go to Step 5;
otherwise, continue.

Step 4. T(TMA) $\leftarrow$ T(FIRST)
FIRST $\leftarrow$ FIRST + 1

Step 5. If TMA = LAST, go to Step 7; otherwise, continue.

Step 6. TMA $\leftarrow$ TMA + 1

Step 7. Exit EZERO.

It is clear that the logic required in Step 3 above is an array of n AND-gates. Unlike most of the procedures discussed so far, the EZERO procedure does not require a final BCF operation; the terms that remain after the procedure is carried out constitute an expression in Blake canonical form.

PROJ. The command

PROJ ,

which we think of as calling for a "projection" of the function stored in

T(SEL) with respect to the variables explicit in TERM, deletes precisely those terms in T(SEL) that are not deleted by the command EZERO. Thus, a term survives the deletions called for by PROJ in case at least one of its variables is explicit in TERM. The steps evoked by PROJ are the same as those evoked by EZERO, with the following modifications:

New Step 3: Change = in old Step 3 to $\neq$.

New Step 4: BCF
Exit PROJ.

<u>IRR</u>. Denote by f the Boolean function represented by the set of terms stored in T(SEL). Then the command

IRR

deletes a subset of those terms in such a way that the surviving terms also constitute a representation of f but that no proper subset of the surviving terms is such a representation. The sum of the surviving set of terms is called an <u>irredundant</u> formula for f. Let us call a term <u>redundant</u> with respect to a given SOP formula if deletion of that term from the formula does not alter the represented function. Ghazala [25] has shown that the term p_1 is redundant with respect to the formula $\sum_{i=1}^{k} p_i$ if and only if the condition $\sum_{i=2}^{k} p_i/p_1 = 1$ is satisfied. The IRR-operation, which is based on Ghazala's theorem, is similar to one implemented in the logical computer TOPI [24]. The first term in T(SEL) is tested to determine whether it is redundant with respect to the sum of the remaining terms; it is deleted from T(SEL) in case it is redundant. The second term is then tested, and deleted in case it is redundant with respect to the terms surviving the first test. The procedure continues until all terms have been tested; the surviving terms constitute an irredundant formula for the function originally stored in T(SEL).

A Boolean function may have many distinct irredundant formulas. The particular irredundant formula produced by IRR depends on the order in which prime implicants are stored in T(SEL). TOPI is able to re-order the prime implicants in its term-memory, in random fashion, in order to generate more than one irredundant formula for a given function; no such provision is presently contemplated for the inferential processor.

The sequence of sub-operations evoked by IRR is detailed below:

Step 1. PUSH
TMA ← FIRST

Step 2. PUSH
TERM ← T(TMA)
DIV

Step 3. If T(FIRST) = 1, continue; otherwise, go to Step 5.

Step 4. POP
T(TMA) ← T(FIRST)
FIRST ← FIRST + 1
Go to Step 6.

Step 5. POP

Step 6. If TMA = LAST, go to Step 8; otherwise, continue.

Step 7. TMA ← TMA + 1
Go to Step 2.

Step 8. Exit IRR.

It should be noted that the foregoing procedure does not include a final BCF operation; a final BCF would undo the effects of IRR by restoring the prime implicants removed by the latter.

VII. APPLICATIONS

We present in this section a number of applications for the proposed inferential processor. The field of logical processing is of course a vast one, and the applications listed here represent just a few that occur to the author as a result of his own experience and interests. It is hoped nevertheless that this section will convey an impression of the potential utility of inferential processing.

The study of applications, necessarily a brief one in the ten weeks allocated for this investigation, has proved most useful in giving the processor design something to chew on. This mastication has revealed a number of errors and omissions, and has suggested several design-features and user-commands not originally contemplated.

Certain of the commands suggested by applications do not appear in Section VI, where the basic commands to the term-processor are listed. It has seemed more appropriate instead to design these higher-level commands essentially as hardware-macros, and to define them in the present section--along with the applications to which they apply.

Solution of Boolean Equations

A fundamental problem in Boolean analysis, one that arises in many contexts and forms, is that of solving a system of Boolean equations and implications. Among the variables $x_1,\ldots,x_n$, a certain number (say $x_1,\ldots,x_m$) are designated as dependent and the remainder, i.e., $x_{m+1},\ldots,x_n$, are designated as independent. The problem is to solve for each of the dependent variables in terms of the independent variables.

This problem was one of the first considered by Boole [3] in elaborating an algebra of logic, and was investigated intensively by Boole's nineteenth century successors. An excellent brief treatment of the theory of Boolean equations is given by Hammer and Rudeanu [27]; for a complete treatment, see Rudeanu [51].

Recent work in the field of digital engineering has emphasized the value of being able to solve Boolean equations. Cerny and Marin [11,13] have given a general technique for synthesizing digital circuits based on solving such equations. In a recent text [58], Svoboda and White supply a family of APL programs for the solution of Boolean equations, and show how these programs may be applied to the synthesis of digital circuits. They note that "the program BOOL can be used for computer-aided design of sequential circuits. The design procedure mentioned here can be applied to any structural type (model). That means the design of circuits with or without memory elements in the feedback loop, clocked as well as non-clocked circuits, can be assisted by these programs. Roughly speaking, the procedure formulates engineering conditions (constraints) of the circuit in the form of Boolean equations and designs the combinational network by solving that system of equations."

The first step in the solution of a system of Boolean equations and implications is to reduce the system to an equivalent single equation of the form

$$\phi(x_1,\ldots,x_n) = 0 \ . \tag{7.1}$$

This process is carried out as a fixed part of any application of the inferential processor; see Section V for details.

The next step is to solve (7.1) for its dependent variables in terms of its independent variables. The inferential processor provides a choice between two forms of solution:

a) particular solutions, and
b) general solutions.

The way in which these two solution-forms are obtained in the inferential processor is described in the following paragraphs.

<u>Particular</u> <u>solutions</u>. Let $x_1,\ldots,x_m$ be dependent variables and let $x_{m+1},\ldots,x_n$ be independent variables. Then a <u>particular</u> <u>solution</u> of the Boolean equation (7.1) is a collection $g_0,g_1,\ldots,g_m$ of (n-m)-variable Boolean functions having the following properties:

(i) equation (7.1) has a solution for $x_1, \ldots, x_m$ in terms of $x_{m+1}, \ldots, x_n$ if and only if the condition

$$g_0(x_{m+1}, \ldots, x_n) = 0 \tag{7.2}$$

is satisfied identically; and

(ii) the function $\phi(g_1(x_{m+1}, \ldots, x_n), \ldots, g_m(x_{m+1}, \ldots, x_n), x_{m+1}, \ldots, x_n)$ is identically zero.

Condition (7.2) is called the consistency-condition for equation (7.1). It is a classical result that g_0 is given by

$$g_0(x_{m+1}, \ldots, x_n) = \prod_{(a_1, \ldots, a_m) \in \{0,1\}^m} \phi(a_1, \ldots, a_m, x_{m+1}, \ldots, x_n) \ . \tag{7.3}$$

To produce a particular solution for a system of Boolean equations, the user first enters the equation into the inferential processor, using the commands discussed in Section V. The subsequent commands and processor-responses are listed below.

Commands	Responses
$x_1 x_2 \ldots x_m$	
EZERO	
OUT	g_0
POP	
$x_2 \ldots x_m$	
EZERO	
x_1	
PSOLN	g_1
$x_3 \ldots x_m$	
EZERO	
x_2	
PSOLN	g_2
.	
.	
.	

x_m

EZERO

x_{m-1}

PSOLN g_{m-1}

1

EZERO

x_m

PSOLN g_m

The first four commands, viz.,

$x_1 x_2 \ldots x_m$

EZERO

OUT g_0

POP

produce the consistency-function, g_0. The remaining commands occur in blocks of four, having the sequence

$x_{i+1} \ldots x_m$

EZERO

x_i

PSOLN g_i

and producing the function g_i (in irredundant SOP form). The subsequence

1

EZERO

in the last block of four commands has no elimination-effect; its function is to put the processor in the proper state to deal with the final two commands.

The command PSOLN is not one of the basic commands described earlier in this report; it is a higher-order command (macro) defined as follows:

```
NTERM
DIV
IRR
OUT
POP
NTERM
ADD
LDM
LDM
EOR
POP
LDM
OR
LDT
EZERO
```

Consider for example the system

$$\begin{aligned} \bar{x}_2x_3 + x_1 &= x_2x_3 \\ x_3 &\leqslant x_4 \\ x_2 &= x_2 + x_4 \ , \end{aligned} \tag{7.4}$$

which reduces to the equivalent single equation

$$x_3\bar{x}_4 + \bar{x}_2x_3 + x_1\bar{x}_2 + x_1\bar{x}_3 + \bar{x}_2x_4 + x_1\bar{x}_4 + \bar{x}_1x_3 = 0 \tag{7.5}$$

(the left-hand side of (7.5) is expressed in Blake canonical form, as it would be expressed in the term-processor). Suppose further that a solution is desired for x_1, x_2, and x_3 in terms of x_4. Such a solution is generated by the following sequence:

Commands	Responses
(enter ∅)	
$x_1x_2x_3$	
EZERO	
OUT	0
POP	

(continued)

x_2x_3	
EZERO	
x_1	
PSOLN	0
x_3	
EZERO	
x_2	
PSOLN	x_4
1	
EZERO	
x_3	
PSOLN	0

The first response indicates that $g_0 = 0$; thus the consistency-condition (7.2) is satisfied identically. The remaining three responses show that a particular solution of (7.4)--or, equivalently, (7.5)--is $x_1 = 0$, $x_2 = x_4$, and $x_3 = 0$. If these substitutions are made in (7.4), the result is an identity.

Suppose now that a solution is desired for x_3 and x_4 in terms of x_1 and x_2. The user would enter the following sequence of commands, and receive the responses indicated:

Commands	Responses
(enter $\emptyset$)	
x_3x_4	
EZERO	
OUT	$x_1\bar{x}_2$
POP	
x_4	
EZERO	
x_3	
PSOLN	x_1
1	
EZERO	
x_4	
PSOLN	x_1

The first response above indicates that the equation (7.5) has a solution for x_3 and x_4 in terms of x_1 and x_2 if and only if x_1 and x_2 satisfy the condition $x_1\bar{x}_2 = 0$. Provided the foregoing condition is satisfied, a particular solution is $x_3 = x_1$, $x_4 = x_1$.

General solutions. A general solution of a Boolean equation is a representation of the set of all of its particular solutions. One such representation, clearly, is an exhaustive enumeration of particular solutions. Suppose, however, that there are n variables, m of which are dependent; then there may be as many as

$$(2^m)^{(2^{n-m})}$$

particular solutions. Enumeration is practical, therefore, only in special cases. An interval-based general solution, however, provides a condensed representation in all cases of the set of solutions--one which indicates the general nature of the particular solutions and provides a convenient way of generating particular solutions if such are desired. Let us assume that the dependent variables are $x_1,\ldots,x_m$ and that the independent variables are $x_{m+1},\ldots,x_n$. Then an interval-based general solution of the equation (7.1) has the form

$$\begin{aligned}
g_0(x_{m+1},\ldots,x_n) &= 0 \\
g_1(x_{m+1},\ldots,x_n) &\leq x_1 \leq h_1(x_{m+1},\ldots,x_n) \\
g_2(x_1,x_{m+1},\ldots,x_n) &\leq x_2 \leq h_2(x_1,x_{m+1},\ldots,x_n) \\
g_3(x_1,x_2,x_{m+1},\ldots,x_n) &\leq x_3 \leq h_3(x_1,x_2,x_{m+1},\ldots,x_n) \\
&\vdots \\
g_m(x_1,\ldots,x_{m-1},x_{m+1},\ldots,x_n) &\leq x_m \leq h_m(x_1,\ldots,x_{m-1},x_{m+1},\ldots,x_n) .
\end{aligned} \tag{7.6}$$

The first statement in the system (7.6) is the consistency condition, given earlier as (7.2). The second statement specifies the range of allowable values of x_1. For any value of x_1 in that range, the third statement specifies the range of allowable values of x_2, and so on.

Suppose as before that the dependent variables are $x_1,\ldots,x_m$, and that one wishes to produce an interval-based general solution of (7.1) using the

inferential processor. To do so, one issues the commands, and receives the responses, that are listed below.

Commands	Responses
(enter ϕ)	
x_m	
GSOLN	g_m
	h_m
	d_m
x_{m-1}	
GSOLN	g_{m-1}
	h_{m-1}
	d_{m-1}
$\vdots$	
x_1	
GSOLN	g_1
	h_1
	$d_1 = g_0$

The responses g_i, h_i, d_i are SOP *formulas*, each involving a subset of the arguments $x_1, \ldots, x_{i-1}, x_{m+1}, \ldots, x_n$. The g_i and the h_i are as indicated in the system (7.6); the d_i are "don't-care" functions applicable to g_i and h_i (the condition $d_i = 0$ may be assumed, that is, in searching for simplified expressions for g_i and h_i). The algorithm that produces the general solution is based on the Blake canonical form for $\phi(x_1, \ldots, x_n)$; this algorithm was developed as a result of earlier research [8].

It would be desirable for the inferential processor itself to employ the don't-care functions $d_1, \ldots, d_m$ in order to produce simplified SOP formulas for the g's and h's. Such a feature, it now appears, would best be obtained by cooperation between the inferential processor and the general-purpose computer to which it is attached.

The command GSOLN is a macro defined as follows:

```
PROJ
NTERM
DIV
OUT
POP
NTERM
DIV
COMP
OUT
POP
POP
EZERO
OUT
```

Let us consider again the system (7.4), which reduces as noted earlier to (7.5). A general solution for x_1, x_2, x_3 in terms of x_4 is produced by the sequence shown below.

Commands	Responses
(enter ∅)	
x_3	
GSOLN	x_1
	$x_1x_2x_4$
	$x_1\bar{x}_2 + \bar{x}_2x_4 + x_1\bar{x}_4$
x_2	
GSOLN	$x_1 + x_4$
	1
	$x_1\bar{x}_4$
x_1	
GSOLN	0
	x_4
	0

The general solution above is represented in more conventional notation as follows, ignoring the don't-care functions:

$$0 = 0$$

$$0 \le x_1 \le x_4$$

$$x_1 + x_4 \le x_2 \le 1$$

$$x_1 \le x_3 \le x_1 x_2 x_4 \quad .$$

The interval $x_1 \le x_3 \le x_1x_2x_4$ may appear inconsistent, inasmuch as x_1 appears to be a "bigger" function than $x_1x_2x_4$. The associated don't-care condition, viz., $x_1\bar{x}_2 + \bar{x}_2x_4 + x_1\bar{x}_4 = 0$, guarantees, however, that x_1 is indeed less than or equal to $x_1x_2x_4$.

Let us now generate a general solution for x_3 and x_4 in terms of x_1 and x_2:

Commands	Responses
(enter ∅)	
x_4	
GSOLN	$x_1 + x_3$
	x_2
	$\bar{x}_2x_3 + x_1\bar{x}_2 + x_1\bar{x}_3 + \bar{x}_1x_3$
x_3	
GSOLN	x_1
	x_1x_2
	$x_1\bar{x}_2$

Expressed conventionally,

$$x_1\bar{x}_2 = 0$$

$$x_1x_2 \le x_3 \le x_1$$

$$x_1 + x_3 \le x_4 \le x_2 \quad .$$

Functional Deducibility

Let variables $x_1,\ldots,x_n$ be related by the constraint

$$\phi(x_1,\ldots,x_n) = 0. \tag{7.7}$$

We say that x_1 is functionally deducible from $x_2,\ldots,x_n$ in case there is an (n-1)-variable Boolean function g such that

$$x_1 = g(x_2,\ldots,x_n). \tag{7.8}$$

We have shown elsewhere [4] that x_1 is functionally deducible from $x_2,\ldots,x_n$ if and only if the identity

$$E_{x_1}\phi(x_1,\ldots,x_n) = 1 \tag{7.9}$$

is fulfilled, in which case (7.8) is valid if and only if g is a function in the nonempty interval

$$\bar{\phi}(1,x_2,\ldots,x_n) \leq g \leq \phi(0,x_2,\ldots,x_n). \tag{7.10}$$

The test (7.9) is implemented by the sequence

Commands	Responses
x_1	
EONE	
TEST1	(YES or NO)

If the response to the foregoing test is YES, then x_1 is functionally deducible; the lower and upper bounds on the function g in that case are produced by the macro DEDUCE, defined as follows:

Commands	Responses
DIV	
COMP	
OUT	(lower bound)
POP	
NTERM	
DIV	
OUT	(upper bound)

Consider for example the design for a D-latch shown in Figure 7.1.

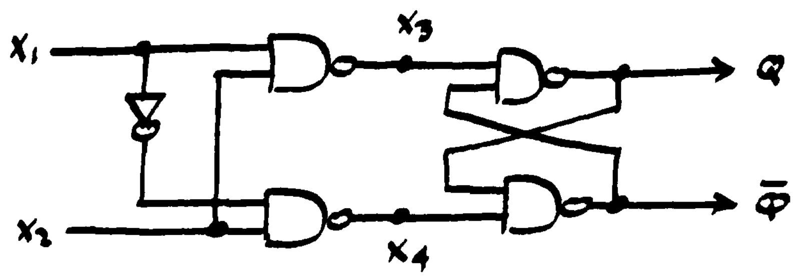

Fig. 7.1. Initial design for D-latch.

This design is specified by the system

$$\begin{aligned} x_3 &= \bar{x}_1 + \bar{x}_2 \\ x_4 &= x_1 + \bar{x}_2 \quad . \end{aligned} \tag{7.11}$$

The DEDUCE command, along with the repertoire of commands for Boolean analysis discussed in Section VI, enables us to experiment with an existing design, seeking improvements. We notice, for example, that the design of Fig. 7.1 comes tantalizingly close to being realizable in a single quad two-input NAND package. The following dialogue with the inferential processor tells us that we can remove the single inverter that stands in the way of such a realization, and tells how to remove it.

	Commands	Responses
1.	ENTER	
2.	x_3	
3.	ENTER	
4.	$\bar{x}_1$	
5.	$\bar{x}_2$	
6.	EOR	
7.	ENTER	
8.	x_4	
9.	ENTER	
10.	x_1	
11.	$\bar{x}_2$	

(continued)

12. EOR

13. OR

14. LDT

15. x_1

16. EZERO

17. x_4

18. EONE

19. TEST1 YES

20. POP

21. x_4

22. DEDUCE $\bar{x}_2 x_3 + x_2 \bar{x}_3$

$\bar{x}_2 + \bar{x}_3$

Commands 1 through 14 above serve to enter the system (7.11) into the inferential processor. We wish to see if x_4, whose generation presently involves inverting x_1, can be realized without using the path from x_1; hence, we eliminate x_1 (steps 15 and 16). In steps 17 through 20, we inquire whether the variable x_4 is functionally deducible from the remaining variables. The reply is YES; therefore we determine (steps 21 and 22) the bounds on x_4. These bounds establish that the simplest function for x_4 is

$$x_4 = \bar{x}_2 + \bar{x}_3 \quad , \tag{7.12}$$

leading to the simplified design shown in Figure 7.2.

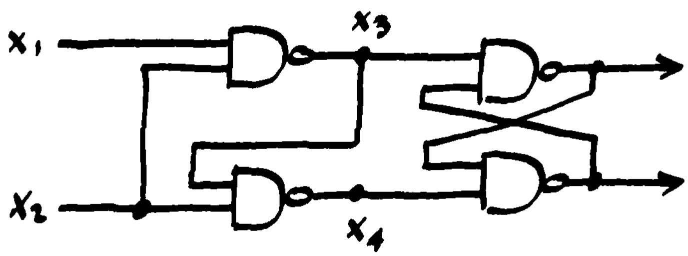

Fig. 7.2. Improved design for D-latch.

Another example is that of designing the logic to produce the overflow-output, V, in a two's-complement adder. This logic is characterized by

the system of Boolean equations

$$
\begin{aligned}
x_4 &= x_1x_2 + x_1x_3 + x_2x_3 \\
x_5 &= x_1 \oplus x_2 \oplus x_3 \\
x_6 &= x_1x_2\bar{x}_5 + \bar{x}_1\bar{x}_2x_5 ,
\end{aligned} \tag{7.13}
$$

where x_1 and x_2 are the input sign-bits; x_3 and x_4 are the input and output carries, respectively, of the sign-adder; x_5 is the output sign-bit; and x_6 is the overflow-function, V. We seek in this case to simplify the form of the output x_6. To do so, we first enter the system (7.13) into the inferential processor. Then we try eliminating variables, one after another, testing after each elimination to see if x_6 is functionally deducible from the remaining variables. If the response is NO, we restore the variable just eliminated (using a POP command); otherwise, we allow the variable to remain eliminated. The foregoing process (we omit the details) reveals that the variables x_1, x_2, and x_5 (all of the variables on which x_6 was specified initially to be dependent!) are eliminable; hence, x_6 is functionally deducible from the remaining variables--x_3 and x_4. The lower and upper bounds are both announced by the inferential processor to be $\bar{x}_3x_4 + x_3\bar{x}_4$; thus, the overflow-function is given uniquely in terms of x_3 and x_4 as

$$
x_6 = x_3 \oplus x_4 . \tag{7.14}
$$

The expression (7.14) is clearly preferable to the third expression of (7.13)

Selective Deduction

A general class of logical problems involves selective deduction from given hypotheses. All applications of the inferential processor may in fact be considered special cases of this class of problems. The following example is a modification of one given by Ledley [31].

Enzyme biochemistry has two characteristic features. First, it is usually difficult to isolate an enzyme in pure form, and thus the chemist must deal with imprecise and indirect knowledge of the enzyme content of the experimental ingredients. Second, usually more than one chemical reaction takes

place at the same time, and even these are observed indirectly.

Suppose a chemist is studying enzymes x_1, x_2, and x_3 in relation to reactions x_4, x_5, and x_6. Suppose further that he has completed the following experiments:

1. $\bar{x}_1\bar{x}_2\bar{x}_3 \leqslant \bar{x}_4 x_5 \bar{x}_6$ — In the first experiment, a solution containing none of x_1, x_2, and x_3 produced reaction x_5 but neither x_4 nor x_6.

2. $x_1(x_2 + x_3) \leqslant \bar{x}_5\overline{(x_4 x_6)}$ — In the second experiment, the solution contained x_1 and either x_2 or x_3, or both (the chemist could not be sure); the reaction was neither x_5 nor was it x_4 and x_6 together.

3. $\bar{x}_1 x_2 + \bar{x}_2 x_3 \leqslant x_4 x_5 + \bar{x}_4 x_6$ — In the third experiment, the solution had x_2 but not x_1, or did not have x_2 but had x_3. Reaction x_4 and x_5 occurred, or reaction x_4 did not occur but x_6 did.

4. $(x_1 + x_2)x_3 + \bar{x}_1\bar{x}_3 \leqslant \bar{x}_4 + x_5 x_6$ — In the fourth experiment, the chemist obtained a solution from a source that had x_3, together with x_1 or x_2 or both, or else had neither x_1 nor x_3. Either reaction x_4 did not take place, or both x_5 and x_6 did.

5. $x_1\bar{x}_2 \leqslant \bar{x}_4 + \bar{x}_6$ — In the fifth experiment, a solution containing x_1 but not x_2 either failed to produce reaction x_4 or failed to produce reaction x_6.

Let us suppose that the chemist, having made the foregoing observations, seeks answers, in the simplest possible form, to the following questions:

1. What is known concerning the reactions x_4, x_5, and x_6, independent of any knowledge of enzyme content?

2. What is known concerning the enzymes x_1, x_2, x_3, given each of the following reactions:
   (a) x_4 occurred;
   (b) x_4 did not occur;
   (c) x_6 occurred;
   (d) x_6 did not occur.

To obtain the answers he seeks, the chemist must first enter the system of inclusions resulting from his experiments (notice that the operation of implication, inherent in the narrative statements, is replaced by the operation of inclusion) into the inferential processor; to do this, he uses the commands discussed in Section V. He then types the following commands, and records the indicated responses:

	Commands	Responses
	(enter ∅)	
1.	$x_1x_2x_3$	
2.	EZERO	
3.	OUT	$x_4\bar{x}_5x_6$
4.	POP	
5.	STO PHI	
6.	$\bar{x}_4$	
7.	ADD	
8.	$x_4x_5x_6$	
9.	EZERO	
10.	OUT	$x_1x_3 + \bar{x}_1\bar{x}_2\bar{x}_3$
11.	RCL PHI	
12.	x_4	
13.	ADD	
14.	$x_4x_5x_6$	
15.	EZERO	
16.	OUT	0
17.	RCL PHI	
18.	$\bar{x}_6$	
19.	ADD	

(continued)

20. $x_4x_5x_6$

21. EZERO

22. OUT $\qquad\qquad\qquad\qquad$ $\bar{x}_1\bar{x}_2\bar{x}_3$

23. RCL PHI

24. x_6

25. ADD

26. $x_4x_5x_6$

27. EZERO

28. OUT $\qquad\qquad\qquad\qquad$ $\bar{x}_1x_2 + x_1\bar{x}_2x_3$

The chemist begins (steps 1 and 2) by eliminating the enzyme-variables. He then requests output (step 3); the processor responds that what is known concerning the reactions, in the absence of knowledge concerning the enzymes, is expressed by the equation $x_4\bar{x}_5x_6 = 0$. Thus, either x_4 does not occur, x_5 does occur, or x_6 does not occur. Stated differently, $x_4x_6 \leq x_5$, i.e., if x_4 and x_6 occur simultaneously, then x_5 occurs also. The POP command (step 4) restores the original function $\emptyset$ for further analysis. In step 5, the chemist stores the function $\emptyset$. To answer question 2a, he wishes to introduce the constraint $x_4 = 1$. Recall, however, that all functions in the inferential processor are presumed to be set equal to zero; thus he introduces the equation $\bar{x}_4 = 0$ (steps 6 and 7). He then eliminates the reaction-variables and asks for output (steps 8 through 10). The response is the Boolean equation $x_1x_3 + \bar{x}_1\bar{x}_2\bar{x}_3 = 0$. This response is equivalent to the simultaneous statements $x_1x_3 = 0$ and $\bar{x}_1\bar{x}_2\bar{x}_3 = 0$. Interpretation is easier, perhaps, in the complemented form $\bar{x}_1 + \bar{x}_3 = 1$ and $x_1 + x_2 + x_3 = 1$. The answer to question 2a, therefore, is that if reaction x_4 occurs, then (i) at least one of the enzymes x_1 and x_3 is not present and (ii) at least one of the enzymes x_1, x_2, and x_3 is present. The user may find the result easier to interpret if it is given in the form

SOP formula = 1 .

To obtain the SOP formula on the left, the user inserts

COMP

OUT

in place of the OUT-command at step 10. The response to OUT would then be the desired SOP formula, viz., $\bar{x}_1x_2 + x_1\bar{x}_2 + x_1\bar{x}_3 + x_2\bar{x}_3$. The answer to 2a is now

put as follows: either (i) x_1 is not present and x_2 is present, or (ii) x_1 is present and x_2 is not present, or (iii) etc. Steps 11 through 16 tell the chemist that if reaction x_4 does not occur then nothing is known concerning the enzyme-content. The remainder of the dialogue provides answers, in the manner discussed above, to questions 2c and 2d.

Adaptive Diagnosis

The Air Force has come to depend heavily on complex digital systems for combat operations, communications, command & control, and analysis of intelligence data. To keep such systems operating, sometimes under adverse conditions, the breakdowns (faults) that occur should be detected--and located, if possible--with the least possible intervention by slow and fallible human beings.

One way to automate the diagnosis of a digital system is to smother it with tests, attempting to exhaust all of its possible modes of behavior. Such complete exhaustion of cases is frequently impractical; hence, a variety of strategems has been developed to get by with fewer tests. One is to carry out a random sample of the possible tests; another is to design, through careful analysis of the structure of the system, a test-set small enough to be practical but large enough to detect all (or a large percentage of) the expected faults.

The foregoing approaches to fault-diagnosis share several drawbacks. One is that few of them make any use of the results of tests already conducted to guide the selection of later tests; most of the tests in a typical test-sequence, as a result, do not reveal anything new. A disadvantage of the non-random and non-exhaustive procedures is that they are almost always based on specialized assumptions, e.g., that no more than one fault can be present. The procedures that locate faults (rather than merely detecting that a fault exists) are accompanied by particularly restrictive assumptions.

A technician attempting to find a trouble in a television receiver, or a physician in a consulting room, employs none of the approaches described above (one hopes). The testing each does is adaptive. Every test resolves a certain

amount of uncertainty. In most cases, therefore, many conceivable subsequent tests (rather than simply the one just performed) are ruled out. The measure of a human diagnostician's skill is that he be able to locate the "faults" in the system in front of him after the fewest possible tests. Tests are costly in time and money; repeated intervention in the operation of the system under diagnosis may often exact a cost of its own; and the diagnostician is presumed to possess abundant powers of deduction.

Automated diagnostic systems are presently forgiven for not having the technician's or physician's ability to home in rapidly on faulty components. One reason for such forgiveness is the difficulty of programming the complex deductive processes required for adaptive testing. Much of this difficulty is removed, however, by the inferential processor.

We describe in this section an approach to adaptive fault-location based on the deductive capabilities of the proposed inferential processor. It is the first application, to the author's knowledge, of a general deductive mechanism to the supervision of a diagnostic process. The model we set up for the system under diagnosis includes, as a special case, combinational logic-networks having multiple stuck-type faults. Not all diagnostic problems, of course, can be put in the format described here; it should be emphasized, however, that the inferential processor is not at all restricted to problems in this format. Only a summary description is presented here; a full report on this approach has been completed [7], however, and is awaiting typing as this report is being written.

A variety of diagnostic tasks may be described in the following general way. A logical system is presented to an experimenter. The system's output, z, is dependent, in a way known to the experimenter, upon (a) manipulable inputs $x_1,\ldots,x_n$ accessible to the experimenter, and upon (b) fixed (but inaccessible) logical parameters $y_1,\ldots,y_m$ having unknown values. The system might be a digital circuit under fault-diagnosis; in this case, the internal parameters represent the states (normal, stuck-at-zero, stuck-at-one) of check-points. The system might also be a patient undergoing medical diagnosis, in which case the logic generating the output represents the body of knowledge linking a certain category of diseases with the associated symptoms. Each of the fixed internal parameters in this case is a disease, which is either present or not present

in the patient. Each combination of manipulable inputs represents a test to elicit a particular symptom; the corresponding output indicates presence or absence of that symptom, for the existing disease-pattern.

The experimenter is assumed to have perfect powers of deduction; his task is to manipulate the inputs, observe the corresponding outputs, and thereby to infer as much as possible concerning possible values of the internal parameters. To do so by exhausting all possible input-combinations is often undesirable (certainly so in the case of medical diagnosis); our recent research on logical inference has yielded a technique, however, that guides the experimenter's choice of input-values in such a way that new information concerning the unknown parameters is guaranteed to be produced at each step in the diagnostic process. Thus all possible information concerning the unknown parameters can be elicited after far fewer tests than are required in exhaustive diagnosis.

An example will indicate the general way in which an inferential processor may be employed as the "experimenter" in such on-line diagnosis. Suppose it is desired to learn as much as can be known about the internal parameters y_1, y_2, y_3 of the system shown in Figure 7.3, and to do so by means of the fewest possible input-output tests.

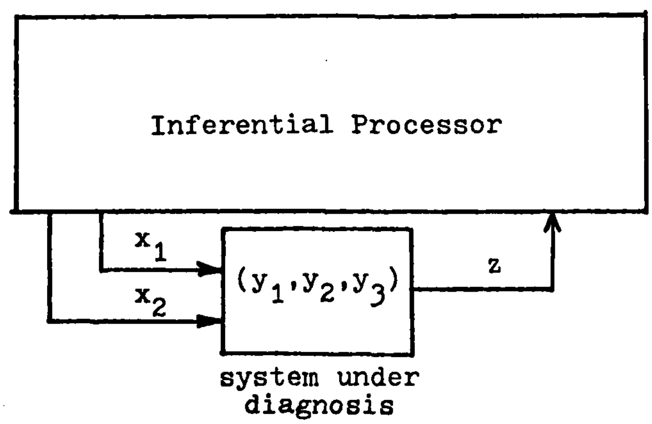

Fig. 7.3. Diagnostic application of inferential processor.

The inferential processor performs each test by controlling the values of the inputs x_1 and x_2 and observing the corresponding values of the output, z. We suppose that the known dependence of the output upon the inputs and the internal parameters is expressed by the Boolean equation

$$z = x_1\bar{y}_1 + \bar{x}_2 y_2 + \bar{x}_1\bar{x}_2 y_3. \tag{7.15}$$

The experimenter is typically in possession of a certain amount of a priori information concerning the internal parameters; thus a check-point in a digital circuit cannot be stuck-at-one and stuck-at-zero simultaneously, and certain disease-patterns in a patient are known not to be possible. Let us assume that what is known initially concerning the parameters of this system is represented by the equation

$$0 = y_1 y_3 , \tag{7.16}$$

i.e., the parameters y_1 and y_3 cannot both have the value 1.

Given the foregoing equations as initial information, and provided with a microprogram made up of suitable commands from those described in Sections V and VI of this report, the processor generates an equation,

$$0 = \bar{x}_1 x_2 \quad ,$$

whose solutions are the effective input-combinations, i.e., the input-patterns guaranteed to elicit additional information about the y's. The processor generates a solution, $(x_1,x_2) = (0,0)$ of the foregoing equation and applies it as a test-input to the system under diagnosis. Suppose this test-input produces the output 1; from this test-outcome, along with the initial equations (7.15) and (7.16), the processor generates an updated equation,

$$0 = \bar{x}_1 + \bar{x}_2 ,$$

characterizing the set of effective input-combinations. The processor generates the unique solution $(x_1,x_2) = (1,1)$ of the foregoing equation and applies it as a new test-input. Suppose the input combination 11 produces the output 1. From this test-outcome, the processor generates the equation

$$0 = 1$$

to specify the set of effective inputs. This equation has no solutions (i.e.,

no test-input can yield further information concerning the y's); hence, the processor terminates the experiment and informs the experimenter that the set of possible y's is given by the Boolean equation

$$0 = y_1 + \bar{y}_2\bar{y}_3 ,$$

i.e., y_1 is known to be at logical zero and at least one of y_2 and y_3 is known to be at logical zero (more convenient output-formats can be microprogrammed if desired; these are discussed in the previous subsection on the solution of Boolean equations). It is typically the case, as above, that the values of the y's cannot be determined uniquely by input-ouput testing. Testing of the kind described above will always determine z, however, as a function of the inputs. In the present case, this dependence is expressed by

$$z = x_1 + \bar{x}_2 .$$

The inferential processor can be microprogrammed, of course, to produce the foregoing output function if it is desired.

VIII. RECOMMENDATIONS

Many ideas have evolved during this project, over a short period of time, concerning logic, machine-design, and applications. To make intelligent recommendations and to suggest appropriate lines of future work requires an interval of contemplation which the schedule of this project does not permit. Some preliminary recommendations, however, can be put forward at this time (a more mature set will be submitted in the near future as part of a proposal to AFOSR).

The central recommendation is that this work proceed. Our initial rather diffuse conception of how a logical processor of general capability might be organized has now crystallized into a scheme which we know to be feasible. The various parts of this scheme, however, are unevenly developed. The whole design, moreover, is still in the "armchair" stage; it is certainly full of errors, lacunae, and insect-life.

Work in four major areas seems appropriate:

1. A detailed study of applications.
2. Software simulation.
3. Development of a programming language.
4. Construction of a pilot model, to be interfaced to a minicomputer.

We discuss these areas in the remainder of this section.

Applications. The study of applications is the best way to locate awkwardness, error, and omission in the design. The applications discussed in Section VII, for example, proved most helpful in exposing inadequacies in versions of this design developed early in the project.

Simulation. A simulator would provide the test-bed for the kind of experiment that exposes error and generates ideas. A great deal of simulation would clearly be required before the design could be considered sufficiently mature to make the construction of a prototype worthwhile.

Programming language. The machine designed during the course of this project operates in what might be called a calculator-mode. The user, in other words, carries out the major sequencing-steps. A command called TEST1, for example, produces a reply of YES or NO, leaving it to the user to decide what to do next. In addition, the user must presently issue what might be called assembly-level commands. To use these commands, the user must have an intimate knowledge of the architecture of the inferential processor. A higher-level programming language is clearly required. The user should be able to write a normal (e.g., FORTRAN) program for the host computer, detouring as needed into the language understood (after compilation) by the inferential processor. This language should enable symbolic addressing and conditional branching. It should be structured, moreover, so that the programmer does not need a detailed knowledge of the architecture of the inferential processor. The syntax for entering systems of Boolean equations should be made more natural; the necessary translation into sequences of signals transmitted from the host computer to the inferential processor can of course be done as part of a process of compilation.

Pilot model. The "Mark I" design discussed in Section IV (a microprogrammed machine employing bipolar sequencers and bit-slice processors) would enable the feasibility of the general concept to be demonstrated, and would provide experimental results on processing-speed.

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FINAL REPORT

MANPOWER ALLOCATION IN ASD'S MATRIX ORGANIZATION

Prepared By:	Richard M. Burton
Academic Rank:	Associate Professor
Department and University:	Graduate School of Business Administration Duke University
Research Location:	Air Force Business Research Management Center (AFBRMC/RDCB) Wright-Patterson AFB, Ohio
USAF Research Colleague:	Major Robert F. Golden
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MANPOWER ALLOCATION IN ASD'S MATRIX ORGANIZATION

by

Richard M. Burton

ABSTRACT

Manpower is the critical scarce resource at ASD. Matrix organization has been increasingly used to obtain a better allocation of manpower and to enhance the manpower mobility in response to changing demands. A more efficient utilization of manpower has been realized.

There are several unique aspects of ASD's matrix. Military and civilians have similar tasks throughout the organization. The ASD matrix is a two level organization: a matrix between functional home office and the SPO, and a second matrix within some SPO's. The first matrix has a major responsibility in planning and allocating manpower. The second is an operating matrix involving coordination problems at the work level. Finally, the matrix growth experience began from a program organization and then created matrix functional home offices.

In this study, manpower planning is described and analyzed for ASD's matrix organization. An organizational enhancement is proposed to obtain information which reveals relative SPO manpower surpluses as well as deficiencies. This information could be used to increase the short term mobility for manpower, and further, the information could be used to help establish organizational priorities in hiring.

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I. INTRODUCTION:

Manpower is the critical scarce resource at Aeronautical Systems Division (ASD). Increasing workload and increasingly varied workload, coupled with a relatively constant workforce, demands that ASD be efficient in its allocation of manpower among the many competing demands. ASD's response to this challenge has been the increasing use of matrix organizations; beginning with the engineering function (EN) in 1964, and since 1976, the contracting and manufacturing functions (PM), and program control function (AC). In 1980, the program offices have been restructured to a mission orientation and fewer single program offices. ASD enters the decade of the 80's with increased demand for efficient use of its manpower and their talents.[1, 3, 10] General Skantze[1] (p. iii) has stated "Overall, the eighties will be a time for renewal of our efforts toward more efficient management of our human resource."

More generally, the challenge at ASD is shared by organizations everywhere. Complex organizations, where productivity is difficult to measure, are becoming the norm. Well over half of working Americans have jobs which are essentially "information processing" in nature. The organizational response has been varied; but invariably organizations are becoming more complex in their departure from the usual hierarchial command and control organization. Matrix organization is one organizational structure which is used widely; government, industry, consulting, higher education, among others. Each application has its own uniqueness and complexity.

The complexity of a matrix is exacerbated by a multiplicity of perceptions of a given organization by individuals within the organization. This might be called a relativity theory of organization. Each individual sees a different organization, depending upon where he/she sits in the organization. At ASD, this phenomenon is particularly evident. Senior collocates see a different "matrix" than home office managers. Individuals within a System Program Office (SPO) see a different matrix real world than either of these. Indeed, this phenomenon is true for any organization, but it is more pronounced for a matrix organization, especially at ASD.

This report is a compilation and synthesis of many individual views at ASD as well as the observations and analysis of the author.

II. Objectives

The primary objective of this study is to describe and analyze matrix management at ASD. As manpower is the critical scarce resource at ASD,[3] the particular focus has been the organizational process for manpower planning and allocation by the matrix organization.

More generally, for the Air Force and society as a whole, the efficient use of human resources in complex organizations is an important managerial challenge. The analysis of the ASD's experience is an important element in an ongoing managerial and research quest to make large complex organizations more efficient.

III. ASD as a Complex Organization

ASD has been previously referred to as a complex organization. At ASD, complexity is revealed in a number of ways:

a. ASD/contractor relations. The buyer/seller relations are very involved. Basically, ASD buys flying machines and associated items which are yet to be precisely specified in either form, performance or cost. In the economist's jargon, it is an ill defined product which yields unusual relations between buyer and seller.[11] ASD operates in a market environment for which the theory is limited, and the practice is very involved.

b. Productivity issues. A central issue at ASD is that individual productivity is difficult to define, to measure, and to aggregate. The nature of the work at ASD is essentially the development of knowledge and information processing. That is, ASD analyzes, designs, coordinates, and controls; it does not make a product, or provide a simple service. The definition and measure of productivity, either at the individual level or organizational level, is neither simple, nor well understood. However, one conclusion is clear. Productivity methods which are relevant for simpler production situations do not transfer to "information" organizations.[2] The general issue is particularly important as more than half of us have such jobs.

c. Matrix organization. The ASD matrix departs from the simpler hierarchial organization. One matrix involves the various SPO's and the functional home offices; EN, PM, and AC. Another matrix organization is found in many SPO's themselves; the "matrix within a matrix." It is well

known[4, 5] that the matrix has a duality of authority and responsibility which creates varying degrees of ambiguity, conflict, uncertainty, opportunity, and hopefully, overall organizational efficiency. Many of these characteristics seem to be at variance with efficiency. Yet, this is not necessarily the situation. Matrix organization requires a deeper look. In addition, the ASD matrix is not the usual matrix organization. It requires individual consideration and analysis. Those issues are considered in more detail next.

IV. The Special Matrix at ASD

The ASD matrix organization has special features which are different than the explicit, or implicit situation presumed in the literature.[4,5] The usual organization is an existing functional organization which is establishing a project/product matrix dimension to the organization, where the goal is to obtain increased operational coordination among the functional units. This is not the ASD situation. Some of those special issues include:

a. Primary goals. The principle reasons for the extension of the matrix to PM and AC in 1976 is to obtain more efficient planning and timely allocation of manpower, as well as strengthening the functional management aspects of ASD and career development for individuals through the establishment of functional home offices for procurement, manufacturing, and program control.[3] These goals are traditional for a matrix organization, but take on special significance at ASD. In many organizations, the goal of the matrix is to involve both the functional home and the project office in the day by day management. At ASD, the matrix goals are to improve the longer term resource planning and allocation, and the establishment of a functional balance in decision making.

b. The critical scarce resource. For ASD, manpower is the critical scarce resource. Consequently, planning in ASD is stated in number and skills of individuals to accomplish given tasks. In most commercial organizations, the budget for functions and projects, frequently stated in dollar terms, is the critical scarce resource. This distinction is more facade than real, and suggests that the behavior concerning budgets in commercial organizations will be similar to the behavior concerning manpower at ASD.

c. The military/civilian organization. The individuals at ASD are military and civilians. Many positions can be filled by either. Yet, the performance evaluation systems, the career paths, and the professional goals of each are different. This situation has its greatest impact upon the performance evaluation systems[9] and will be discussed in some detail.

d. The matrix growth path. The Air Force pioneered and developed the SPO organization. The matrix at ASD required the establishment of the functional home offices; EN, PM, and AC. The more usual situation has been the establishment of the project/product office in an organization where there existed strong functional home offices. At first glance, these are simply symmetrical situations. But a deeper look suggests the symmetry is not simple. The growing problems of the two situations are quite different. This characteristic alone makes the ASD experience particularly interesting.

e. The two levels of the matrix decisions. At ASD, there are two levels of decisions. One is the planning matrix which plans and allocates manpower from the functional home offices to the Deputates. The second level is the operating matrix which deals with the day by day management problems. Although not exclusively, the planning matrix idea captures the relation between the functional home offices and the Deputates. An individual is assigned to a Deputate for an indefinite period of time. This may be short in terms of a month or two, or perhaps for a few years.

A second matrix relation is found within some Deputates where there is a "matrix within a matrix." That is, the Deputate itself is a matrix organization. The senior collocate is the functional manager. This matrix is an operating matrix and does deal with day by day issues and very short term assignment of individuals to tasks. Detailed coordination at the work level is managed. This matrix form has been enhanced by the 1980 change to create mission oriented Deputates. This characterization of matrix relations does not imply that the functional home office and Deputate relation is exclusively planning, nor the internal Deputate matrix is exclusively operating. Clearly, this is not the case, but it captures significant concerns and decisions of each.

This study concentrates on the longer term planning matrix between the functional home offices and the Deputates at ASD. Further, the author spent most of his time with PM and AC, and thus, the analysis may not reflect accurately the EN situation.

V. Individual Performance Evaluation in the ASD Matrix

In any matrix organization, performance evaluation is difficult. ASD is no exception.[6,9] ASD has accepted the challenge, and the current system is perceived as much better than the one of very recent years.

Briefly, the officer effectiveness report (OER) for the military is written by the immediate supervisor, and the endorsement chain follows the Deputate hierarchy. For exceptional cases of outstanding performance, etc., the functional home augments and substantiates the rating. For the civilians, an individual's immediate supervisor writes the performance evaluation, and the endorsement is made within the Deputate and co-signed by the functional home office. Initially, the differences between the military and civilian procedures may seem incongruous.

The rationale for the current system rests upon two criteria:

a. The evaluation is written by the individual with the most direct information about performance, and

b. The evaluation procedure fits the career demands of the individual.

The individual's performance evaluation should reflect his/her productivity. Previously, it has been argued that productivity is extremely difficult to measure. Under these conditions, the immediate supervisor has good information about the individual. However, this does imply that the immediate supervisor can make equitable evaluations without aid or review. Due to subjectivity of the ratings, interpersonal comparisons can be misleading and unfair. Two raters may disagree about a given individual's performance; or, two raters may agree about performance, but interpret the scales differently. Norms are developed through application of the rating system, not by regulation. To guard against the potential inequities, the initial ratings are monitored by the functional home office for civilians. For the military, the monitoring seems less well defined.

The endorsement chain reflects the differing career demands of the miltary and civilians. Both are professionals, but the dimensions are different. The civilian career is more oriented to a functional specialty; as contracting, manufacturing, control, etc. The military career involves less concern for a functional specialty; and more concern for a series of varied assignments with more emphasis on command. (Of course, there are exceptions to this simplified view.) The current endorsement chain attempts

to reflect the individual career demands and the differing environmental demands, e.g., the Air Force's officer career situation.

The current system, although not without controversy, is generally accepted. This is a major achievement; regardless of the rationale for the system. Yet, the rationale is important. The ASD rationale based upon who has the information for the evaluation and the monitoring, coupled with a response to individual's career demands, is appropriate.

VI. The Manpower Planning Matrix at ASD

Manpower planning and allocation is a primary activity in the functional home office and SPO matrix at ASD. The remainder of this study focuses on the planning matrix for manpower allocation. The study considers in some detail the various manpower models at ASD, and the organizational process of allocating manpower. The decision making process includes the use of the model, but the models do not make decisions.

VII. Manpower Models

There are a number of manpower models at ASD. In each case, the model is an attempt to derive a manpower requirement as a function of the task, or workload assignment. The models themselves are different in detail and form.

a. For PM:

1. Workload assignment model (WAM). The WAM is the manpower model devised by the contracting home office to assess the manpower requirements for a SPO. The model is:

$$\text{Direct hours} = \sum_{\text{tasks}} \text{Standard} \times \text{Task quantity}$$

There are 17 different task categories, or document categories. Each task category has an empirically determined standard. Direct hours are calculated for each task as the standard times the task quantity, and then summed for all tasks. These total direct hours are then increased by an indirect factor to determine a total manning requirement. The indirect factor differs among SPO's. Currently, the task quantities (required documents of varying types) is taken from the Automated Management Information

System (AMIS). The Little AMIS (LAMIS), which gives a statement of authorized tasks to be accomplished, will be used in the near future.

The contracting home office also performs detailed on site workload assessments for: (a) adjusting the WAM results with more detailed information, and (b) adjusting the task standards and indirect rates for the WAM.

2. Workload assessment program (WAP). The WAP is the manpower model used by the manufacturing home office. The current model is a modification to include quality assurance of the proposed model devised by Morris and Franke.[8] In contrast to the WAM, the WAP approach does not use standards. The WAP approach begins with a determination of the work to be done, e.g., source selection support, negotiation, producibility analysis, manufacturing assessment, etc. There are some 25 tasks. Using these tasks, the home office estimates total manhours to accomplish the tasks. In essence, the equivalent of standards are determined by the home office personnel on an individual situation basis. The total direct manhours are supplemented by supervisory and support personnel estimates. The resulting document gives a required manpower by skill listing.

b. For AC:

AC workload survey. The AC workload survey is a team review approach. The team assesses the work to be done and then estimates the manning required to accomplish the work. The team members must be knowledgeable. Essentially, the team is required to apply its expertise, derived from experience, to estimate requirements. Each AC team (usually three people) includes both home office individuals and individuals from a SPO, other than the SPO under review.

The PM and AC models and surveys are used as an element to the manpower allocation process. The organizational process is discussed in more detail later.

There are other manpower models. The Management Engineering Team at ASD (MET-30) has the Systems Acquisition Manpower (SAM) model.[2] It is a multivariate single equation regression model. The parameters in the model were determined from historical data gathered prior to April 1977. The model logic is to determine manpower requirements from a list of drivers. From a list of 17 potential drivers, the ASD single project SPO has three significant drivers, engineering complexity, program funding, and contractor capability. For a basket SPO, there are 10 signficiant drivers from the possible 17.

There have been other manpower regression models attempted for ASD. Detailed documentation is not readily available.

VIII. Models and the Decision Making Process

The Manpower models at ASD are not used as answers for manpower allocations, but more as indicators about where knowledgeable individuals should look deeper. The models themselves are only part of a complex decision making process which will be discussed in the next section.

There is a continuing search for a mathematical manpower model which will give a believable, accurate answer, i.e., a model which will make good decisions. This is a noble task, but unlikely to be fully successful. The required model will contain parameters and variables which are numerical measures of work. That is, work must be described, e.g, documents processed, and then the work must be converted to manhours, e.g., it takes 20 manhours to process one document. For most information processing organizations, an operational definition of work, and consequently a measure of productivity is wanting.

Another modeling approach has been to use indicators as drivers, e.g., engineering complexity. Although the indicators certainly influence manpower requirements, it is very difficult to develop operational scales to measure the indicators.

The result is that the manpower models cannot be used unmonitored as answers. But, they can be efficient ways to ask questions, and indicate where to look more deeply. The models cannot be judged alone as their value depends upon how they are used together with more detailed assessment methods. At ASD, both the benefits and the limitations are realized. The models are used to initiate more in-depth analysis and negotiation.

IX. Organizational Decision Making for Manpower

The PM and AC models are used as a part of a negotiation process between the functional home office and the SPO senior collocates, at least. There are a number of steps.

Usually, the Deputate will initiate a request for additional manpower. This request is sent to the functional home office for review and action. The SPO request is based upon its own independent assessment of the workload and associated manpower requirements. It is not an attempt to duplicate the home office models. In some cases, the SPO analytical independence is intentional and purposeful to maintain its own objectivity in assessing requirements. In Figure 1, a (-1) represents a SPO request.

Upon receipt of the request, the home office reviews the request in detail. The home office can respond in one of two ways: the argument is insufficient, or the transfer of an individual from one SPO to another. In Figure 1, the +1, -1 in row B represent the functional home office's concurrence of a transfer. This individual transfer requires the agreement of the SPO directorate who loses the individual as well. There is one exception. The contracting home office has a surge force for assignment to a SPO on a short term basis.

For the home office, there are two issues in the process:

a. Does the request represent a relative priority, and

b. How to choose the individual (and SPO) for the transfer. (i.e., where to put the +1 in Figure 1)

The general criterion is to balance the resources at an "equal hurt" level.* The results of the models are used to indicate whether the request seems reasonable; and further, to indicate where to look for individuals to transfer. It is not implied that the models are used to make either decision, but they are indicators. The home office managers consider the entire set of information to determine the relative priorities.

The system incentives and the total manpower constraints do not encourage the most efficient use of limited manpower.[7] The home office normally reacts to SPO requests, and finds substantial resistance to reallocations generated from its own analysis. The home office must allocate limited manpower among competing demands, and determine the relative priorities. The home office assumes a policing role. The SPO incentive is to keep the manpower it has, and augment the manning when a good case can be made. Consequently, the SPO incentive is to "stockpile" manpower. There are good reasons to do so. First, the SPO has lost an individual and obtains nothing in return. Second, there is a possible future workload increase which will create difficulties. The safe response is to keep all manpower; whether fully utilized, or not. This is perfectly reasonable, but it is not necessarily efficient. The surge force in the contracting home office has softened the extent to which the SPO's are reluctant to release individuals, as the surge force is used to respond rather quickly to surge workload demands.

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* This could be interpreted as equal marginal disutility.

Functional Home Office	SPO 1.	2.	3.
A			
B	+1		-1 (-1)
C			(-1)

Figure 1: Current Decision Process

<u>Key</u>: negative numbers represent relative deficiency
positive numbers represent relative surplus
( ) represents SPO requests
without ( ) represents home office requests

However, many individuals at ASD believe that the current organizational process is not as responsive to changing workload as it could be. The hypothesis can be stated; programs are relatively understaffed in the early life; and relatively overstaffed during the phase down. That is, there is a lag in response to changing workload demands. This hypothesis is shown pictorially in Figure 2.

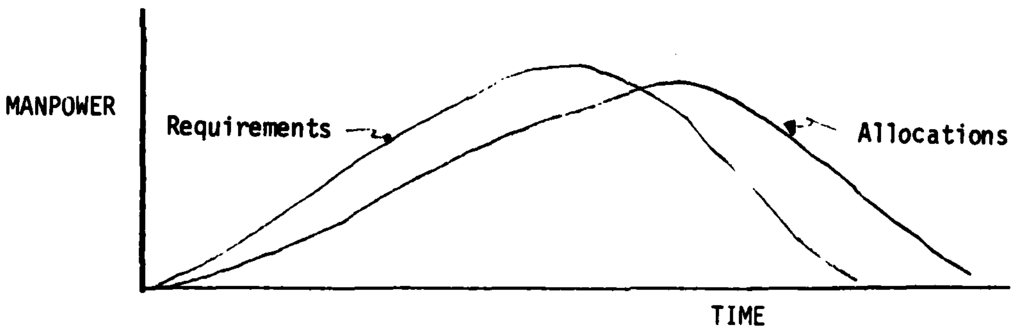

Figure 2: Project Manpower Requirements and Allocations

X. Enhancing the Timeliness of Manpower Transfers

The efficiency of the manpower at ASD would be improved by a more timely identification of the relative priorities and the associated transfers. In Figure 2, the allocations curve would be moved to the left and placed more closely in line with the requirements. It is generally accepted at ASD that the present matrix organization has moved the allocations and requirements closer together than would be the situation without the functional home offices.[3] Further, within mission SPO's, the manpower mobility has been increased at the operating matrix level. Therefore, the approach is to enhance the existing system to achieve increased timeliness and increased efficiency.

The approach is to ferret out additional information about the relative priorities in the workload. As has been argued throughout, the best information exists at the project level, i.e., where both workload requirements and productivity are best known. This information then becomes the basis for the project to determine its own relative priorities in terms of manpower requirements.

A proposed increase in manpower in a functional area by a project office would be accomplished by a proposed transfer of an individual in a different functional area.* This is not to say there is not work for the individual--it is simply a statement of relative priority. Based upon projected workload and productivity estimates, the project office can determine the priority skills to get the job done. In Figure 3, under column 3, the project office indicates a priority for an individual from home office B in lieu of an individual from home office C. That is, the project office would prefer the change to the current situation.

Will the change enhance the timliness of proposed manpower transfers? The identification of the relative surplus is revealed much earlier than under the current system where home office C would eventually ferret out the relative surplus. That is, in Figure 3, the +1 in row C, Col 3, is known now rather than later. For home office C, this individual is identified immediately and is available for transfer to a higher priority which home office C may have identified.

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*Functional area is not strictly home office, as the project office might propose an exchange within a home office, e.g. within PM, the project office might propose an exchange of a contracting individual for a manufacturing individual.

Functional Home Office (rows) × **SPO** (columns)

	1.	2.	3.
A			
B	+1		-1 (-1)
C			(+1)

Figure 3: Enhanced Decision Process

<u>Key</u>: negative numbers represent relative deficiency
positive numbers represent relative surplus
( ) represents SPO requests
without ( ) represents home office requests

Figure 4 shows a larger set of priorities for manpower and suggests tentative interpretations.

This process assumes that there is a fixed number of individuals in each functional home office. It also assumes each SPO has a fixed allocation of manpower. The transfers (+1, -1) are to be accomplished within these constraints.

This process operates on a continuing basis with requests for transfers being accomplished at any point in time.

This change is an attempt to elicit additional relevant information about relative manpower priorities from project offices. The timeliness of the information for manpower mobility yields added efficiency to the existing organizational process.

Functional Home Office (rows) × **SPO** (columns)

	1.	2.	3.
A	(+1)	+1 (+1)	-1 (+1)
B	+1(-1)		-1 (-1)
C	+1	-1 (-1)	

Figure 4: Priorities and Tentative Interpretations

C-2, B-3	priority transfers
A-2	relative surplus
A	relative surplus home office
B	relative deficient home office
3	relative deficient SPO
1	relative surplus SPO

XI. Constraints and Longer Term Adjustments

Over a longer term (e.g., 6 months), the allocations within the fixed manpower constraints may become imbalanced (i.e., the +, - requests cannot be realized within the constraints.) For example, in Figure 4, home office B has a relative deficiency within the constraints, and home office A a relative surplus. Similarly, SPO 3 has a relative deficiency vis-a-vis SPO 1. As this imbalance continues to build up, this would signal that the constraints themselves need review and possible adjustment. The command level at ASD would then review these trends to determine if the trends reflect its own priorities as well. The command could then adjust the SPO manpower constraints and the functional home office constraints. The relatively deficient SPO would obtain an increased manpower constraint which would be filled according to process which considers both the SPO and functional home office priorities. The functional home office B has the relative deficiency and its total manpower allocation would be increased. A's allocation would be decreased. At ASD, function B would have priority in hiring. Function A would not replace attritions.

The above analysis assumes that the workload at ASD is reasonably constant. A new program, or a change in status of an existing program, e.g. begin production, signals an adjustment in relative priorities and calls for a change in the SPO manpower allocations. The SPO with the new or augmented program would obtain an increased allocation; some other SPO would be decreased. For a mission SPO, the command may decide to let the adjustment take place within the SPO itself. Thus, the SPO constraints would remain unchanged.

These command level changes in manpower allocations of the functional home offices and the SPO create the constraints for a new round of adjustment and relative prioritization by the SPO's and home offices.

The process operates on a continuing basis among SPO's and home offices with a periodic review and possible adjustment at the command level.

XII. Recommendations

The matrix organization at ASD has increased the timeliness of manpower transfers and increased the efficient use of ASD's limited human resources. The challenge is to ferret out additional relevant information which will enhance the timeliness of transfers and lead to increased efficiency. One

organizational process is proposed which elicits relative manpower priorities from the SPO's and integrates that information with priorities established by the functional home office. It augments the existing organizational processing in an attempt to increase the mobility of the limited manpower.

In more general terms, the efficient utilization of critical scarce manpower is a challenge for all information processing organizations. We are limited to suggest more effective organizational processes to obtain greater efficiency. There is a continuing need for the development of better manpower models. But it is equally important to understand and improve the organizational processes which allocate manpower. The models and the processes may be considered together as it is the organizational application of the model which determines utility. There is a need for further research in this area which addresses both manpower models and organizational decision making processes.

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FINAL REPORT

FOURIER TRANSFORM INFRARED SPECTROSCOPY ANALYSIS OF MNA

Prepared by:	Dr Joseph F. Chiang
Academic Rank:	Professor
Department and University:	Department of Chemistry State University of New York
Research Location:	Air Force Rocket Propulsion Laboratory, Chemical Research and Development Section
USAF Research Colleague:	Dr C. I. Merrill

Date:	July 12, 1980
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FOURIER TRANSFORM INFRARED SPECTROSCOPY ANALYSIS OF MNA

by

Joseph Chiang

ABSTRACT

A method was devised based on Fourier Transform Infrared (FTIR) spectroscopic technique to analyze the low concentration, carcinogenic, anti-oxidant, N-methyl-p-nitroaniline (MNA) in solid rocket propellant. The sliced propellant was extracted by chloroform in a Soxhlet extract tube at 60oC for 24 hours. The extracted MNA was turged with dry nitrogen to remove the solvent. Then 6.0 ml chloroform was added and the absorbents of this solution were measured using two minutes of FTIR scanning time in a 0.143 mm KBr cell. 65% of MNA was recovered based on a 0.2% MNA in the original propellant. Detailed procedure for this extraction was prepared for futre analysis of MNA in solid propellant.

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FINAL REPORT

Submitted To: Director, Summer Faculty Research Program

Submitted By: Joseph F. Chiang, SFRP Associate

The objective of this summer research was to devise a method for the analysis of a solid propellant anti-oxidant by Fourier Transform Infrared (FTIR) spectroscopic technique (Nicolet MX-1). In order to accomplish a complete extraction of the antioxidant from solid propellant, the solubilities of the antioxidant, N-methy p-nitroaniline (MNA) in various solvents were examined. The following solvents were chosen and tested: benzene, carbon tetrachloride, diethyl ether, methylene chloride, dichlorethane, and chloroform. Chloroform was found to be a suitable solvent for the extraction because MNA dissolved in chloroform instantaneously and that chloroform had a simple noninterfering spectrum. A 1% MNA chloroform solution was prepared and analyzed by FTIR. This spectrum of MNA was obtained by subtracting the chloroform reference spectrum from the 1% MNA spectrum. The spectrum clearly indicated the N-H peak of MNA at 3453 cm^{-1}. This peak was used for the identification of MNA. More dilute solutions of MNA were also prepared as follows: 0.1%, 0.02%, and 0.004% MNA, all in chloroform. The 0.1% solution produced a clearly visible N-H peak at 3453 cm^{-1} in a 0.025mm BaF_2 cell using sixty-four signal averaged spectra acquired during two minutes scanning time. Six-hundred forty signal averaged spectra accumulated over twenty minutes were needed to produce a clearly visible N-H peak for the 0.02% MNA solution in the same cell. Under these conditions the 0.004% MNA solution did not show a N-H peak.

In order to further prove that the N-H peak was a unique peak for the purpose of identifying the presence of MNA, oxidation of MNA was carried out with N_2O_4 and N_2O_3. These reagents generated N-nitroso and N-nitro products in which adsorptions at 3453 cm^{-1} were absent. As a further check to confirm that the

3453 cm^{-1} absorption was due to a N-H structure rather than a nitrosoamine structure, a spectrum of N-nitrosodimethylamine was recorded. An infrared band at 3453 cm^{-1} was not observed.

The initial attempt at extracting MNA from solid propellant was by ultrasonic agitation of 10 ml of chloroform over about 2.5 gm solid propellant shavings. MNA was not detected even with six-hundred forty signal averaged spectra of the chloroform extract. The plasticizer, trimethylol ethane trinitrate (TMETN), was readily detected. In order to minimize solvent interference and improve detectability the solvent was evaporated from the extract on a KBr plate. The infrared spectrum showed TMETN without any indication of the presence of MNA.

The apparent absence of MNA in the chloroform extract generated a concern that the MNA may have combined chemically with another component in the solid propellant, most likely the aziridine curative (HX-868). To test this possibility a mixture of aziridine and MNA in a 1:2 mole ratio was prepared. The mixture was stored in a controlled oven at 60°C for six days. A spectrum of the mixture was recorded periodically. Since the magnitude of the 3453 cm^{-1} N-H peak did not change with time, it was concluded that chemical reaction between the curative and MNA did not occur at a significant rate.

Since a mass spectrometer was expected to have much lower MNA detectability limit than the FTIR, a mass spectrum of material remaining after solvent evaporation of the extract was obtained. The appearance of a mass 152 ion (parent ion) confirmed the presence of MNA in the extract. A rough estimate of 1:40 was obtained for the MNA to TMETN ratio. These results demonstrated that the MNA concentration in the extract was too low for detectability by the FTIR.

Early solvent studies indicated that MNA was carbon tetrachloride insoluble. Since the plasticizer, TMETN, was very soluble in carbon tetrachloride, initial extraction with carbon tetrachloride followed by chloroform extraction held

promise for obtaining a more concentrated MNA in the extract. This method was tested by first conducting a Soxhlet extraction of a propellant sample with carbon tetrachloride. The carbon tetrachloride did remove nearly all of the TMETN. A mass spectrometer test of the carbon tetrachloride extract did not indicate the presence of MNA. A subsequent extraction with chloroform similar to that used earlier did not result in FTIR detectable amounts of MNA. Twenty minute FTIR runs compiling six-hundred forty spectra were obtained for the extract in 0.025 mm and 0.143 mm cells and with a solvent evaporated sample on a potassium bromide plate. Mass spectrometer analysis, however, indicated the presence of MNA along with small amounts of TMETN. At a 0.2% MNA concentration 2.5g of solid propellant could have yielded up to five milligrams of MNA. According to FTIR data obtained with MNA standards five milligrams MNA in ten milliliters chloroform should have been readily detectable. This provided evidence that the simple one step extraction process was very inefficient for removing MNA from the solid propellant.

For purposes of comparison a liquid chromatographic (HPLC) technique was simultaneously employed for the detection of MNA and separation from TMETN. Approximately, one gram of the propellant was extracted for sixteen hours with ten milliliters of glyme (1, 2-dimethoxyethane). MNA and TMETN samples were collected from HPLC separation of four one-hundred microliter injections of extract. The separating element was a 4.6 x 250 mm, non-polar, bonded, reversed phase column (Hewlett-Packard #79918A, 10 micron silica support). A mobile phase composition of 30% methanol-70% water increased stepwise to 45% methanol after 15 minutes at a flow rate of 1.00 ml/min was employed. Sample detection was by 254 nm light absorption. Tentative identification of the MNA peak was made by retention time compared to an authentic MNA sample. Identification of TMETN was made by FTIR. Although the collected MNA sample was too small to be detected by the FTIR, a mass

spectrum of the HPLC MNA sample confirmed that the collected peak was indeed MNA.

To get MNA concentrations so that the FTIR could be used for the analysis a manual, multiple step extraction was used as follows: 0.688 gram of thinly sliced propellant sample was extracted by 5.0 ml chloroform for a few days. The chloroform solution was decanted and saved in a stoppered flask. An additional 5.0 ml chloroform was added to the propellant in a repeat of the first extraction. This process continued for four weeks until ten extractions were completed with a total chloroform volume of 50.0 ml. The combined extracts were evaporated to dryness by a stream of dry nitrogen. Five ml chloroform was added to dissolve the dried residue. A 0.143 mm KBr cell was used with a two minute scanning period to obtain a signal averaged spectrum. After subtraction of chloroform and TMETN reference spectra, a MNA spectrum was obtained. The sample spectrum contained a very distinctive peak at 3453 cm^{-1} due to MNA. When extractions were performed as above over a one week period, the MNA concentration was too weak to be detected by the FTIR.

To shorten the manual, four weeks extraction period for a FTIR analysis of MNA in solid propellant, a twenty-four hour Soxhlet extraction of solid propellant with chloroform at 60°C was carried out. The chloroform extract was evaporated to dryness by a dry nitrogen purge, and the residue dissolved in 6.0 ml of fresh chloroform. A 0.143 mm KBr cell with a two minute scanning time was used to obtain an infrared spectrum of the extract. A substantial absorption at 3453 cm^{-1} confirmed adequate MNA concentration. At this point a method for extraction and FTIR analysis for MNA in solid propellant was assured. Detailed procedures will be presented in a separate section.

A quantitative method was developed for estimation of MNA extracted from solid propellant. Standards containing 5×10^{-4} g/ml, 1.0×10^{-3} g/ml and

2.0×10^{-3} g/ml were prepared in chloroform solvent. Two minute FTIR transmission spectra were recorded for each concentration in a 0.143 mm KBr cell. A calibration chart was constructed by plotting the absorbance of the 3453 cm^{-1} band as ordinate vs the concentration of MNA in g/ml as abscissa. A straight calibration line was obtained. Thus, the concentration of an unknown could be found by locating the unknown's absorbance at 3453 cm^{-1} on the calibration line and reading the corresponding concentration for that point.

In one experiment 3.623 g of solid propellant was Soxhlet extracted with chloroform at 60°C for 24 hours. The resulting MNA solution was purged with dry nitrogen to remove the solvent. Fresh chloroform was added to make up a total volume of 6.0 ml. The absorbance of this solution was measured using two minutes of FTIR scanning time in the 0.143 mm cell. An absorbance value of 0.925 was obtained. When referenced to the calibration chart, a MNA concentration of 7.9×10^{-4} g/ml was acquired. Since the total sample volume was 6.0 ml, a total of 4.74 mg MNA had been recovered. Assuming 0.2% MNA in the solid propellant, the expected amount of MNA in the sample was 7.24 mg. This data indicates that the extraction efficiency was about 65%.

ANALYSIS OF N-METHYL-p-NITROANILINE (MNA)

IN NITRATE ESTER PROPELLANTS

(COURIER TRANSFORM INFRARED SPECTROSCOPIC METHOD)

1. Principle

This method is based on the Fourier Transform Infrared (FTIR) spectroscopic technique to analyze the anti-oxidant, N-methyl-p-nitroaniline (MNA), in solid propellants. The propellants to be analyzed were extracted by a suitable solvent. Chloroform was selected for extraction. MNA is extractable and its spectrum can be recorded in a KBr cell. The spectrum of the solvent, chloroform can also be recorded. By substracting the chloroform spectrum from the MNA solution spectrum a pure MNA spectrum can be obtained. A characteristic peak of MNA at 3543 cm^{-1} was used to identify MNA.

2. Reagents and Apparatus

a. Chloroform, spectroscopic grade,

b. Soxhlet extraction tube, condenser, 100 ml round bottom flask, magnetic stirrer, heating mantle, voltage control unit (powerstat) and 22 x 80 mm Whatman cellulose extraction thimbler,

c. Fourier Transform Infrared spectrometer-Nicolet MX-1 or equivalent,

d. 0.15 mm KBr cell.

3. Procedure

The propellant to be analyzed was sliced to a thickness of 40 microns. Soxhlet extraction apparatus was assembled with 100.0 ml flask, heating mantle, voltage control unit (powerstat), and a magnetic stirrer. About 3.5 grams of the solid propellant was weighed to 0.001 g. Extraction thimble size 22 x 80 mm was used to contain the propellant in the Soxhlet extraction tube. A total volume of 100.0 ml $CHCl_3$ was used for the extraction. The apparatus with the propellant to be extracted was heated to about 60°C for 24 hours. The final

extract was evaporated after completion of the extraction to dryness using a nitrogen purge. Then 5.0 ml of fresh chloroform was added to dissolve the residue. A 0.15 mm KBr cell was filled with the final extract in chloroform. A spectrum of the extract was recorded. Chloroform was used as a reference spectrum. By substracting the reference spectrum from the extract spectrum, an MNA spectrum was obtained. The peak at 3543 cm^{-1} was used to indicate the presence and quantity of MNA.

4. <u>Quantitative Method for Estimating the Amount of MNA Extracted</u>

A method was developed to estimate the amount of MNA extracted from the above method. This method is based on the linearity of the absorbance in IR spectra vs the concentration of MNA. A series of known concentrations of MNA in chloroform were prepared in terms of grams per ml. FTIR transmittance spectra were recorded for each concentration. A calibration curve was constructed by plotting the absorbance as ordinate vs the concentration of MNA in g per ml solvent as abscissa. A straight line of calibration was obtained according to Beer's Law. The concentration of an extract could be estimated by using the calibration chart: e.g., locate the absorbance of the extract in the calibration curve; read the MNA concentration on the abscissa corresponding to the absorbance point on the calibration line in grams per ml. This value, multiplied by the final volume of the extract gives the amount of MNA obtained from a given sample of propellant.

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FINAL REPORT

AN ALTERNATIVE TO EXISTING STRATEGIES FOR PERSONNEL SELECTION AND CLASSIFICATION

Prepared by: Dr. Richard E. Christ

Academic Rank: Professor

Department and University: Department of Management, New Mexico State University

Research Location: Air Force Human Resources Laboratory, Manpower and Personnel Division, Force Acquisition Branch

USAF Research Colleague: Dr. Lonnie D. Valentine, Jr.

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ALTERNATIVES TO EXISTING STRATEGIES FOR PERSONNEL SELECTION AND CLASSIFICATION

by

Richard E. Christ

ABSTRACT

It has been suggested that computer-assisted testing of perceptual and psychomotor abilities will provide data which will lead to an improvement of prediction of learning and performance criteria. A review of relevant literature supports that suggestion. Furthermore, the literature review suggests that selected measures of performance from relatively complex tasks will yield information concerning different components of performance when they operate in combination and concurrently. Two experiments were designed to examine a domain of multiple component behavior which is central to the efficient operation of complex man-machine systems. Suggestions for further research in this area are offered.

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I. INTRODUCTION

A research program currently underway at the Manpower and Personnel Division of the Air Force Human Resources Laboratory (AFHRL) is concerned with the investigation, development, and evaluation of computer-assisted testing procedures for personnel selection and classification. One objective of that program is to develop alternatives to existing paper-and-pencil testing procedures. Of particular concern to the Air Force is that measures of perceptual and psychomotor abilities be developed for inclusion into batteries of psychological tests.

Recent research has demonstrated the efficacy of both computer-assisted testing techniques and the use of perceptual and psychomotor test content. Three studies have shown that global measures of complex psychomotor performance yield measures of abilities which are untapped by conventional paper-and-pencil tests.[5,6,9] Furthermore, scores obtained on the computer-administered performance tests added significantly to the prediction accuracy of paper-and-pencil tests for graduation from undergraduate pilot training. Batteries of up to nine computer-administered performance tests have also been developed for experimental use.[3,7] These tests batteries include a variety of perceptual, memory, learning, and motor tasks. It was shown that performance on these test batteries is useful for predicting course grades for officer navigator training and for airmen technical training.[4,7] The U. S. Navy also has developed a performance test battery that is administered by computer. The Navy test battery was able to measure at least two unique abilities.[2] Furthermore, scores on the Navy battery substantially enhanced the prediction accuracy of paper-and-pencil tests for one occupational group, and they were a useful supplement to paper-and-pencil tests for identifying personnel skilled for seven common job elements.[1]

While these recent investigations are very encouraging, substantial additional research is required to fully explicate the value of computer-administered testing of complex human performance capabilities. My background of research in the area of human information processing skills, and my interest in problems encountered in operational environments,

resulted in my applying for and subsequently being assigned to this area of research.

II. OBJECTIVES OF THE RESEARCH EFFORT

A. Specific major research assignments, duties, and responsibilities included: (1) Consultation on and participation in development of the Branch's computer-based test research laboratory, (2) Planning, design, and conduct of major research studies for the purpose of developing alternatives to existing strategies for personal selection, assignment, and utilization. The research effort was to be conducted through the automated test research laboratory and was to provide demonstration of utility of the facility in advancing knowledge with respect to measurement techniques.

B. In addition to the major objective described above, another objective was to become generally acquainted with research and technical programs currently underway at the Manpower and Personnel Division of the AFHRL. This secondary objective required a review of recent technical reports and consultation with supervisory personnel in each branch and section of the Division.

C. Following a general introduction to current work efforts in the Division, several specific areas were targeted for in-depth study assignments. The scientific and technical activities which were the focus of this objective included (1) computerized adaptive testing, (2) judgment analysis and policy specification, (3) estimation procedures using Kalman filters, (4) evaluation of raters and rating procedures, and (5) the Advanced Personnel Data System - Procurement Management Information System (APDS-PROMIS).

III. ALTERNATIVES TO EXISTING STRATEGIES FOR PERSONNEL SELECTION AND CLASSIFICATION

In the past, paper-and-pencil tests were assumed to measure individual differences in mental abilities or "traits," while performance tests were assumed to measure individual differences in perceptual-psychomotor

or "skills." In addition, a collection of relatively independent tests were thought necessary to assess each trait or skill domain. Finally, within tests, the testing material (i.e., the stimuli) and the response alternatives were generally limited to relatively simple, discrete events or a series of discrete events. With one exception, the same conditions for selection and classification are still prevelant in the current operational testing environment. Due to methodological problems associated with the perceptual-psychomotor testing apparatus, the so-called apparatus tests were dropped from operational use in the mid-1950's. Hence, during the past 25 years, there have been no direct operational tests of perceptual-psychomotor abilities.

There are, however, at least three reasons to justify a re-examination of these strategies for personnel testing. First, modern computer-aided testing capabilities no longer impose methodological limits in our attempts to improve selection strategies. The computerized equipment is very reliable and quite portable. Furthermore, these hardware systems can be easily programmed to control the presentation of complex stimuli to subjects and to obtain fine-grained measures of complex responses made by the subject.

Second, contemporary theories of human information processing performance provide new insights for identifying important components of human capabilities. Equally important on the practical side is the argument that human capabilities are not utilized in isolation, but that they operate in combination and concurrently. As noted by Passey and McLaurin,[8] the integrative behavior required of and displayed by operators in complex man-machine systems make it doubtful that performance on isolated tests provide the predictive efficiency required for selection purposes. Hence, from both a theoretical and a practical point of view, the distinction between and the independent assessment of mental traits and perceptual-motor skills is no longer desirable.

Third, a number of experimental and statistical procedures have been developed to isolate the integrative components of human performance. Fine-grained analysis of performance in complex tasks can isolate several measures of component abilities. Recent multivariate techniques permit